Journal of The Chemical Society

DETROIT PUBLIC LIBRARY
JUN 17 1961
TECHNOLOGY DEPARTMENT

May 1961

XUM

PUBLICATION COMMITTEE

Chairman

D. H. Hey, D.Sc., F.R.I.C., F.R.S.

G. O. Aspinall, D.Sc., F.R.S.E., F.R.I.C.
Wilson Baker, M.A., D.Sc., F.R.S.
R. P. Bell, M.A., F.R.S.
E. Boyland, D.Sc., Ph.D.
D. M. Brown, Ph.D.
G. M. Burnett, Ph.D., D.Sc.
I. G. M. Campbell, B.Sc., Ph.D.
N. Campbell, D.Sc., Ph.D.
N. B. Chapman, M.A., Ph.D., F.R.I.C.
J. Chatt, M.A., Sc.D., F.R.I.C., F.R.S.
D. D. Eley, Sc.D., Ph.D.
D. H. Everett, M.B.E., M.A., D. Phil.
R. H. Hall, Ph.D., A.R.C.S., F.R.I.C.
T. G. Halsall, Ph.D., M.A., A.R.I.C.
D. J. G. Ives, D.Sc., A.R.C.S., F.R.I.C.
A. W. Johnson, Sc.D., Ph.D., A.R.C.S.
C. Kemball, M.A., Ph.D., F.R.I.C.
J. A. Kitchener, D.Sc., Ph.D.
G. Kohnstam, Ph.D.
H. C. Longuet-Higgins, M.A., D.Phil., F.R.S.
B. Lythgoe, M.A., Ph.D., F.R.I.C., F.R.S.
H. T. Openshaw, M.A., D.Phil.
M. W. Perrin, C.B.E., M.A., F.R.I.C.
R. A. Raphael, D.Sc., A.R.C.S., F.R.I.C.
P. L. Robinson, D.Sc., F.R.I.C.
K. Schofield, Ph.D., D.Sc., F.R.I.C.
A. G. Sharpe, M.A., Ph.D., F.R.I.C.
J. C. Speakman, M.Sc., Ph.D., D.Sc.
K. W. Sykes, M.A., D.Phil.
Sir Alexander Todd, M.A., D.Sc., F.R.S.
B. C. L. Weedon, D.Sc., A.R.C.S., F.R.I.C.
D. H. Whiffen, M.A., D.Phil.
M. C. Whiting, M.A., Ph.D., A.R.C.S.
G. Wilkinson, Ph.D., A.R.C.S.

Editor

R. S. Cahn, M.A., D.Phil.Nat., F.R.I.C.

Deputy Editor

L. C. Cross, Ph.D., A.R.C.S., F.R.I.C.

Assistant Editors

A. D. Mitchell, D.Sc., F.R.I.C.
I. J. Cantlon, M.A.

Subscription rate to non-Fellows £20 0s. 0d. (including Proceedings) per annum post free.

XUM

XUM

XUM

CONTENTS

General, physical, and inorganic

NO.		PAGE
366	The reaction of diboron tetrachloride with ethylene oxide By A. G. Massey and A. K. Holliday	1893
371	Solvent-extraction of septivalent rhenium. Part I. Heterogeneous equilibria in the system, aqueous nitric acid–potassium perrhenate–tributyl phosphate By A. S. Kertes and A. Beck	1921
372	Solvent-extraction of septivalent rhenium. Part II. Heterogeneous equilibria in the system, aqueous nitric acid–potassium perrhenate–" tri-iso-octylamine " By A. S. Kertes and A. Beck	1926
379	Magnetic perturbation of singlet–triplet transitions. Part V. Mechanism By D. F. Evans	1987
380	The preparation and properties of chelated sulphatobis(ethylenediamine)cobalt(III) salts By C. G. Barraclough and M. L. Tobe	1993
381	Basic tin(II) nitrate By J. D. Donaldson and W. Moser	1996
382	Ruthenium red By J. M. Fletcher, B. F. Greenfield, C. J. Hardy, D. Scargill, and J. L. Woodhead	2000
383	The oxidation–reduction potentials of some copper complexes By B. R. James and R. J. P. Williams	2007
384	Metal complexes of bis-[3-di(carboxymethyl)aminopropyl] ether. The computation of stability constants with the aid of a high-speed digital computor By H. Irving and M. H. Stacey	2019
386	The vapour pressure of plutonium tetrafluoride By C. J. Mandleberg and D. Davies	2031
387	Transition-metal complexes of seven-membered ring systems. Part IV. Proton resonance spectra of cycloheptatriene complexes of group VI metals By M. A. Bennett, L. Pratt, and G. Wilkinson	2037
396	Complexes of tetrahydrothiophen oxide By Ronald Francis and F. Albert Cotton	2078
401	Dinitrogen trioxide. Part IV. Composition of the vapour in equilibrium with liquid mixtures of nitrogen dioxide and nitric oxide By I. R. Beattie and A. J. Vosper	2106
402	Electron-donor and -acceptor complexes with aromatic systems. Part VI. Complexes of nonacyclic aromatic molecules By N. D. Parkyns and A. R. Ubbelohde	2110
403	Studies with dithizone. Part IX. The absorption spectra of mono- and di-*p*-bromo-substituted dithizones and of their metal complexes By H. Irving and R. S. Ramakrishna	2118
407	Mechanism of replacement of chlorine in *cis*- and *trans*-chloronitrobis(ethylenediamine)cobalt(III) ions by thiocyanate in methanol By S. Ašperger, D. Pavlović, and M. Orhanović	2142
412	The hydrogen bonding of imidazole in carbon tetrachloride solution By D. M. W. Anderson, J. L. Duncan, and F. J. C. Rossotti	2165
416	Cyclic anhydrides in sulphuric acid By J. A. Leisten	2191
417	Boron hydride derivatives. Part VII. The characterisation of some decaborane derivatives of the type, $B_{10}H_{12}.2M$ By R. J. Pace, J. Williams, and R. L. Williams	2196

XUM

NO. PAGE

419 Kinetics of the reaction of alkyl and aryl compounds of the nickel group with pyridine
By F. Basolo, J. Chatt, H. B. Gray, R. G. Pearson, and B. L. Shaw . . 2207

420 Thermodynamics of ion association. Part VII. Some transition-metal oxalates
By A. McAuley and G. H. Nancollas 2215

424 The thermodynamic properties of organic oxygen compounds. Part II. Vibrational assignment and calculated thermodynamic properties of phenol
By J. H. S. Green 2236

Notes

425 Thermodynamic properties of organic oxygen compounds. Part III. Formic acid
By J. H. S. Green 2241

427 Stability constants of some metal complexes of *ortho*-aminophenols
By D. D. Perrin 2244

429 Nitromethane: second virial coefficients
By G. A. Bottomley and I. H. Coopes 2247

430 A new stereospecific reaction
By H. Irving and R. D. Gillard 2249

434 Ethylene-platinous chloride pyridine *N*-oxide
By Leonardo Garcia and Milton Orchin 2254

438 Bis(triphenylphosphine)nickel dinitrosyl
By W. P. Griffith, J. Lewis, and G. Wilkinson 2259

Physical organic

365 The gaseous oxidation of isopropyl alcohol. Part I. The influence of temperature, pressure, and mixture composition on the formation of hydrogen peroxide and other products
By A. R. Burgess, C. F. Cullis, and E. J. Newitt 1884

367 Structural correlations in the nuclear magnetic resonance spectra of bisbenzylisoquinoline and aporphine alkaloids
By I. R. C. Bick, J. Harley-Mason, N. Sheppard, and M. J. Vernengo . . 1896

370 The infrared spectra of some oxamides and thio-oxamides
By Brian Milligan, E. Spinner, and J. M. Swan 1919

373 Cyclic organic boron compounds. Part V. Infrared spectra of borazoles and boroxoles
By D. W. Aubrey, M. F. Lappert, and H. Pyszora 1931

374 Conversion of cyclopentadiene into new bicyclopentyl derivatives; structure determination with the help of proton magnetic resonance spectroscopy
By C. F. Blakely, R. J. Gillespie, L. Roubinek, A. Wassermann, and R. F. M. White 1939

375 Kinetics and mechanism of the formation of a novel bicyclopentyl derivative: rôle of carbonium ions in the reaction between cyclopentadiene and trichloracetic acid
By C. F. Blakely and Albert Wassermann 1946

376 Preparation and properties of deeply coloured, electrically conducting polymers
By P. V. French, L. Roubinek, and A. Wassermann 1953

377 Mechanism of formation of a deeply coloured electrically conducting polymer
By J. Murphy, L. Roubinek, and A. Wassermann 1964

378 The crystal and molecular structure of (+)-10-bromo-2-chloro-2-nitrosocamphane
By G. Ferguson, C. J. Fritchie, J. Monteath Robertson, and G. A. Sim . 1976

388 Activation parameters for S_N1 solvolysis in 50% aqueous acetone
By E. F. Brittain, G. Kohnstam, A. Queen, and B. Shillaker . . . 2045

391 The polymerization of 3-substituted oxazolidine-2,5-diones
By C. H. Bamford, H. Block, and A. C. P. Pugh 2057

392 Steric effects on the spectra of aromatic hydrocarbons
By R. I. T. Cromartie and J. N. Murrell 2063

XUM

NO. PAGE

395 The ultraviolet absorption of isolated double bonds
By J. H. CHAPMAN and A. C. PARKER 2075

409 Infrared spectra and structure of arylazonaphthols
By K. J. MORGAN 2151

410 Reactions of αα-diphenyl-β-picrylhydrazyl with phenols
By J. C. McGOWAN and T. POWELL 2160

411 Spectroscopic studies of quarternary aldoximes and ketoximes
By P. W. SADLER 2162

413 The kinetics of complex-formation of 1,3,5-trinitrobenzene with diethylamine and other amines in solution at low temperatures
By C. R. ALLEN, A. J. BROOK, and E. F. CALDIN 2171

421 The transmission of polar effects through aromatic systems. Part I. Substituted anthracenes
By R. O. C. NORMAN and P. D. RALPH 2221

NOTE

433 3-Nitro-2-naphthoic acid
By R. D. TOPSOM and J. VAUGHAN 2253

Organic

358 Gallotannins. Part I. Introduction: and the fractionation of tannase
By E. HASLAM, R. D. HAWORTH, K. JONES, and H. J. ROGERS 1829

359 Gallotannins. Part II. Some esters and depsides of gallic acid
By E. HASLAM, R. D. HAWORTH, S. D. MILLS, H. J. ROGERS, and (in part) R. ARMITAGE and T. SEARLE 1836

360 Gallotannins. Part III. The constitution of Chinese, Turkish, sumach, and tara tannins
By R. ARMITAGE, G. S. BAYLISS, J. W. GRAMSHAW, E. HASLAM, R. D. HAWORTH, K. JONES, H. J. ROGERS, and T. SEARLE 1842

361 Gallotannins. Part IV. The biosynthesis of gallic acid
By E. HASLAM, R. D. HAWORTH, and P. F. KNOWLES 1854

362 Steroidal sapogenins. Part XL. Reaction of 12-oxo-sapogenins with selenium dioxide: synthesis of 3β-hydroxypregna-5,9(11),16-trien-20-one from botogenin
By A. BOWERS, E. DENOT, MARIA BLANCA SANCHEZ, F. NEUMANN, and CARL DJERASSI 1859

363 The chemotherapy of schistosomiasis. Part IV. Some ethers of 4-amino-2-methoxyphenol
By R. F. COLLINS and M. DAVIS 1863

364 Proof of rear approach in the oxidation of ergosterol
By F. DALTON and G. D. MEAKINS 1880

368 The nucleotide sequence in deoxyribonucleic acids. Part V. The alkaline degradation of apurinic acids
By C. R. BAYLEY, K. W. BRAMMER, and A. S. JONES 1903

369 Synthesis of *NN*-dialkyl-*N'*-arylalkyl-*N'*-4-quinazolyl(or 6-methyl-4-pyrimidyl or 4-methyl-2-pyrimidyl)ethylenediamines of potential pharmacological interest
By N. B. CHAPMAN and H. TAYLOR 1908

385 The nature of the Porter–Silber reaction
By D. H. R. BARTON, T. C. McMORRIS, and R. SEGOVIA 2027

389 The isolation and structure of gafrinin, a sesquiterpenoid lactone from *Geigeria africana*
By J. P. DE VILLIERS 2049

390 Syntheses of peptidyl-nucleotidates including L-arginyl-L-alanyl-L-arginyl-L-alanyl uridine-5′ phosphate
By G. HARRIS and I. C. MACWILLIAM 2053

393 Sulphur chloride pentafluoride: reaction with unsaturated hydrocarbons
By J. R. CASE, N. H. RAY, and H. L. ROBERTS 2066

XUM

NO.		PAGE
394	Sulphur chloride pentafluoride: reaction with fluoro-olefines By J. R. CASE, N. H. RAY, and H. L. ROBERTS	2070
397	The preparation of mixed pinacols by cathodic reduction. Part II. By M. J. ALLEN, W. G. PIERSON, and (MISS) J. A. SIRAGUSA	2081
398	The isolation of festuclavine and two new clavine alkaloids from *Aspergillus fumigatus* Fres By J. F. SPILSBURY and S. WILKINSON	2085
399	Modified steroid hormones. Part XXI. 17β-Hydroxy-11-methylene and -11β-methyl-5α-androstan-3-one By D. N. KIRK and V. PETROW	2091
400	Heterocyclic derivatives of guanidine. Part II. Some derived products By J. E. BANFIELD	2098
404	The adducts from triphenylphosphine and dimethyl acetylenedicarboxylate By A. W. JOHNSON and J. C. TEBBY	2126
405	The use, in Wittig reactions, of phosphonium salts and phosphobetaines containing a basic group By S. TRIPPETT and D. M. WALKER	2130
406	Synthesis and stereochemistry of heterocyclic phosphorus compounds. Part II. Loss of optical activity in the reduction of (+)-2-carboxy-9-phenyl-9-phosphafluorene 9-oxide By I. G. M. CAMPBELL and J. K. WAY	2133
408	Derivatives of benzo-1,4-dioxan. Part V. By P. M. HEERTJES and H. C. A. VAN BEEK	2148
414	Synthesis of 4-*O*-(β-D-glucopyranosyl)-D-ribitol, a degradation product of the ribitol teichoic acid from the walls of *Bacillus subtilis* By J. BADDILEY, J. G. BUCHANAN, and F. E. HARDY	2180
415	Biformene By R. M. CARMAN and P. K. GRANT	2187
418	Polyfluoroarenes. Part III. A new synthesis of hexafluorobenzene By J. M. BIRCHALL, R. N. HASZELDINE, and A. R. PARKINSON	2204
422	The resolution of chlorpheniramine and pheniramine By J. H. HUNT	2228
423	The reaction of α-pinene with lead tetra-acetate By G. H. WHITHAM	2232

NOTES

426	Heterocyclic compounds of chalcone type By Z. S. ARIYAN and H. SUSCHITZKY	2242
428	The synthesis of bergamottin By A. CHATTERJEE and (MISS) B. CHAUDHURY	2246
431	10-Methylphenanthridine By M. S. GIBSON	2249
432	Applications of the " abnormal " Reimer–Tiemann reaction By M. S. GIBSON	2251
435	Reaction products from mesityl oxide and lithium By N. BACON, S. BREWIS, G. E. USHER, and E. S. WAIGHT	2255
436	Tetramethylethylene sulphate By WILSON BAKER and B. F. BURROWS	2257
437	Carcinogenic nitrogen compounds. Part XXX. 2,3-Dipyridylquinoxalines and 5,6-dipyridylpyrido(2′,3′-2,3)pyrazines By NG. PH. BUU-HOÏ and G. SAINT-RUF	2258

INDEX OF AUTHORS' NAMES

ALLEN, C. R., Brook, A. J., and Caldin, E. F., 2171
Allen, M. J., Pierson, W. G., and Siragusa, J. A., 2081
Anderson, D. M. W., Duncan, J. L., and Rossotti, F. J. C., 2165
Ariyan, Z. S., and Suschitzky, H., 2242
Armitage, R., Bayliss, G. S., Gramshaw, J. W., Haslam, E., Haworth, R. D., Jones, K., Rogers, H. J., and Searle, T., 1842
Armitage, R. See also Haslam, E., 1836, 1854
Ašperger, S., Pavlović, D., and Orhanović, M., 2142
Aubrey, D. W., Lappert, M. F., and Pyszora, H., 1931
Bacon, N., Brewis, S., Usher, G. E., and Waight, E. S., 2255
Baddiley, J., Buchanan, J. G., and Hardy, F. E., 2180
Baker, W., and Burrows, B. F., 2257
Bamford, C. H., Block, H., and Pugh, A. C. P., 2057
Banfield, J. E., 2098
Barraclough, C. G., and Tobe, M. L., 1993
Barton, D. H. R., McMorris, T. C., and Segovia, R., 2027
Basolo, F., Chatt, J., Gray, H. B., Pearson, R. G., and Shaw, B. L., 2207
Bayley, C. R., Brammer, R. W., and Jones, A. S., 1903
Bayliss, G. S., see Armitage, R., 1842
Beattie, I. R., and Vosper, A. J., 2106
Beck, A. see Kertes, A. S., 1921, 1926
Bennett, M. A., Pratt, L., and Wilkinson, G., 2037
Bick, I. R. C., Harley-Mason, J., Sheppard, N., and Vernengo, M. J., 1896
Birchall, J. M., Haszeldine, R. N., and Parkinson, A. R., 2204
Blakely, C. F., Gillespie, R. J., Roubinek, L., Wassermann, A., and White, R. F. M., 1939
Blakely, C. F., and Wassermann, A., 1946
Block, H. see Bamford, C. H., 2057
Bottomley, G. A., and Coopes, I. H., 2247
Bowers, A., Denot, E., Sanchez, M. B., Neumann, F., and Djerassi, C., 1859
Brammer, K. W., see Bayley, C. R., 1903
Brewis, S. See Bacon, N., 2255
Brittain, E. F., Kohnstam, G., Queen, A., and Shillaker, B., 2045
Brook, A. J. See Allen, C. R., 2171
Buchanan, J. G. See Baddiley, J., 2180
Burgess, A. R., Cullis, C. F., and Newitt, E. J., 1884
Burrows, B. F. See Baker, W., 2257
Buu-Hoï, Ng. Ph., and Saint-Ruf, G., 2258
Caldin, E. F. See Allen, C. R., 2171
Campbell, I. G. M., and Way, J. K., 2133
Carman, R. M., and Grant, P. K., 2187
Case, J. R., Ray, N. H., and Roberts, H. L., 2066, 2070
Chapman, J. H., and Parker, A. C., 2075
Chapman, N. B., and Taylor, H., 1908
Chatt, J. See Basolo, F., 2207
Chatterjee, A., and Chaudhury, B., 2246
Chaudhury, B. See Chatterjee, A., 2246
Collins, R. F., and Davis, M., 1863
Coopes, I. H. See Bottomley, G. A., 2247
Cotton, F. A. See Francis, R., 2078
Cromartie, R. I. T., and Murrell, J. N., 2063
Cullis, C. F. See Burgess, A. R., 1884
Dalton, F., and Meakins, G. D., 1880
Davies, D. See Mandleberg, C. J., 2031
Davis, M. See Collins, R. F., 1863
Denot, E. See Bowers, A., 1859
de Villiers, J. P., 2049
Djerassi, C. See Bowers, A., 1859
Donaldson, J. D., and Moser, W., 1996
Duncan, J. L. See Anderson, D. M. W., 2165
Evans, D. F., 1987
Ferguson, G., Fritchie, C. J., Robertson, J. M., and Sim, G. A., 1976
Fletcher, J. M., Greenfield, B. F., Hardy, C. J., Scargill, D., and Woodhead, J. L., 2000
Francis, R., and Cotton, F. A., 2078
French, P. V., Roubinek, L., and Wassermann, A., 1953
Fritchie, C. J. See Ferguson, G., 1976
Garcia, L., and Orchin, M., 2254
Gibson, M. S., 2249, 2251
Gillard, R. D. See Irving, H., 2249
Gillespie, R. J. See Blakely, C. F., 1939
Gramshaw, J. W. See Armitage, R., 1842
Grant, P. K. See Carman, R. M., 2187
Gray, H. B. See Basolo, F., 2207
Green, J. H. S., 2236, 2241
Greenfield, B. F. See Fletcher, J. M., 2000
Griffith, W. P., Lewis, J., and Wilkinson, G., 2259
Hardy, C. J. See Fletcher, J. M., 2000
Hardy, F. E. See Baddiley, J., 2180
Harley-Mason, J. See Bick, I. R. C., 1896
Harris, G., and MacWilliam, I. C., 2053
Haslam, E., Haworth, R. D., Jones, K., and Rogers, H. J., 1829
Haslam, E., Haworth, R. D., and Knowles, P. F., 1854
Haslam, E., Haworth, R. D., Mills, S. D., Rogers, H. J., Armitage, R., and Searle, T., 1836
Haslam, E. See also Armitage, R., 1842
Haszeldine, R. N. See Birchall, J. M., 2204
Haworth, R. D. See Armitage, R., 1842, and Haslam, E., 1829, 1836, 1854
Heertjes, P. M., and van Beek, H. C. A., 2148
Holliday, A. K. See Massey, A. G., 1893
Hunt, J. H., 2228
Irving, H., and Gillard, R. D., 2249
Irving, H., and Ramakrishna, R. S., 2118
Irving, H., and Stacey, M. H., 2019
James, B. R., and Williams, R. J. P., 2007
Johnson, A. W., and Tebby, J. C., 2126
Jones, A. S. See Bayley, C. R., 1903
Jones, K. See Armitage, R., 1842, and Haslam, E., 1829
Kertes, A. S., and Beck, A., 1921, 1926
Kirk, D. N., and Petrow, V., 2091
Knowles, P. F. See Haslam, E., 1854
Kohnstam, G. See Brittain, E. F., 2045
Lappert, M. F. See Aubrey, D. W., 1931
Leisten, J. A., 2191
Lewis, J. See Griffith, W. P., 2259
McAuley, A., and Nancollas, G. H., 2215
McGowan, J. C., and Powell, T., 2160
McMorris, T. C. See Barton, D. H. R., 2027
MacWilliam, I. C. See Harris, G., 2053
Mandleberg, C. J., and Davies, D., 2031
Massey, A. G., and Holliday, A. K., 1893
Meakins, G. D. See Dalton, F., 1880
Milligan, B., Spinner, E., and Swan, J. M., 1919

XUM

Mills, S. D. See Haslam, E., 1836
Morgan, K. J., 2151
Moser, W. See Donaldson, J. D., 1996
Murphy, J., Roubinek, L., and Wassermann, A., 1964
Murrell, J. N. See Cromartie, R. I. T., 2063
Nancollas, G. H. See McAuley, A., 2215
Neumann, F. See Bowers, A., 1859
Newitt, E. J. See Burgess, A. R., 1884
Norman, R. O. C., and Ralph, P. D., 2221
Orchin, M. See Garcia, L., 2254
Orhanović, M. See Ašperger, S., 2142
Pace, R. J., Williams, J., and Williams, R. L., 2196
Parker, A. C. See Chapman, J. H., 2075
Parkinson, A. R. See Birchall, J. M., 2204
Parkyns, N. D., and Ubbelohde, A. R., 2110
Pavlović, D. See Ašperger, S., 2142
Pearson, R. G. See Basolo, F., 2207
Perrin, D. D., 2244
Petrow, V. See Kirk, D. N., 2091
Pierson, W. G. See Allen, M. J., 2081
Powell, T. See McGowan, J. C., 2160
Pratt, L. See Bennett, M. A., 2037
Pugh, A. C. P. See Bamford, C. H., 2057
Pyszora, H. See Aubrey, D. W., 1931
Queen, A. See Brittain, E. F., 2045
Ralph, P. D. See Norman, R. O. C., 2221
Ramakrishna, R. S. See Irving, H., 2118
Ray, N. H. See Case, J. R., 2066, 2070
Roberts, H. L. See Case, J. R., 2066, 2070
Robertson, J. M. See Ferguson, G., 1976
Rogers, H. J. See Armitage, R., 1842, and Haslam, E., 1829, 1836
Rossotti, F. J. C. See Anderson, D. M. W., 2165
Roubinek, L. See Blakely, C. F., 1939, French, P. V., 1953, and Murphy, J., 1964
Sadler, P. W., 2162
Saint-Ruf, G. See Buu-Hoï, Ng. Ph., 2258
Sanchez, M. B. See Bowers, A., 1859
Scargill, D. See Fletcher, J. M., 2000
Searle, T. See Armitage, R., 1842, and Haslam, E., 1836
Segovia, R. See Barton, D. H. R., 2027
Shaw, B. L. See Basolo, F., 2207
Sheppard, N. See Bick, I. R. C., 1896
Shillaker, B. See Brittain, E. F., 2045
Sim, G. A. See Ferguson, G., 1976
Siragusa, J. A. See Allen, M. J., 2081
Spilsbury, J. F., and Wilkinson, S., 2085
Spinner, E. See Milligan, B., 1919
Stacey, M. H. See Irving, H., 2019
Suschitzky, H. See Ariyan, Z. S., 2242
Swan, J. M. See Milligan, B., 1919
Taylor, H. See Chapman, N. B., 1908
Tebby, J. C. See Johnson, A. W., 2126
Tobe, M. L. See Barraclough, C. G., 1993
Topsom, R. D., and Vaughan, J., 2253
Trippett, S., and Walker, D. M., 2130
Ubbelohde, A. R. See Parkyns, N. D., 2110
Usher, G. E. See Bacon, N., 2255
van Beek, H. C. A. See Heertjes, P. M., 2148
Vaughan, J. See Topsom, R. D., 2253
Vernengo, M. J. See Bick, I. R. C., 1896
Vosper, A. J. See Beattie, I. R., 2106
Waight, E. S. See Bacon, N., 2255
Walker, D. M. See Trippett, S., 2130
Wassermann, A. See Blakely, C. F., 1939, 1946, French, P. V., 1953, and Murphy, J., 1964
Way, J. K. See Campbell, I. G. M., 2133
White, R. F. M. See Blakely, C. F., 1939
Whitham, G. H., 2232
Williams, J. See Pace, R. J., 2196
Williams, R. J. P. See James, B. R., 2007
Williams, R. L. See Pace, R. J., 2196
Wilkinson, G. See Bennett, M. A., 2037, and Griffith, W. P., 2259
Wilkinson, S. See Spilsbury, J. F., 2085
Woodhead, J. L. See Fletcher, J. M., 2000

XUM

PAPERS ACCEPTED

Solid transitions in mixed crystals of ethylene dichloride and ethylene dibromide. By J. E. Spice, G. A. Harrow, C. R. McGowan, and E. B. Smith

Reactions at position 1 of carbohydrates. Part I. The polarographic reduction of carbohydrates. By W. G. Overend, A. R. Peacocke, and J. B. Smith

The kinetics of the decomposition of stannane on a tin surface. By S. F. A. Kettle

Cyclohexane-1,3-diones. Part VI. Structural requirements for the displacement of the alkoxyl by the cyano group in the enolethers of cyclic β-diketones. By B. E. Betts and W. Davey

Cyclohexane-1,3-diones. Part VII. Reaction of 3-methoxy-2,4-diphenylcyclohex-2-en-1-one with acetone cyanohydrin. By B. E. Betts and W. Davey

Pyrylium salts obtained by diacylation of olefins. Part II. The two pyrylium salts formed in diacetylation of 2-methylbut-2-ene. By A. T. Balaban and C. D Nenitzescu

Pyrylium salts obtained by diacylation of olefins. Part III. Diacylation of cyclic olefins and a novel synthesis of isoquinoline derivatives. By A. T. Balaban and C. D. Nenitzescu

Pyrylium salts obtained by diacylation of olefins. Part IV. Di- and tri-acetylation of allylbenzene. By A. T. Balaban, C. D. Nenitzescu, M. Gavat, and G. Mateescu

Reaction of pyrylium salts with alkali cyanides. By A. T. Balaban and C. D. Nenitzescu

The synthesis of some new phenols. By R. E. Dean, A. Midgley, E. N. White, and D. McNeil

Reactions with asymmetric diarylethylenes. Part VI. Reduction of 2-bromo-1,1-di-*p*-alkoxyphenylethylenes by thiophenols, and addition of these thiols to 1,1-di-*p*-alkoxyphenylethylenes. By Wadie Tadros and Camil Aziz

Reduced cyclic compounds. Part XII. Further Diels–Alder reactions of 1-1′-acetoxyvinylcyclohexene. By M. F. Ansell and B. A. Knights

Steroids and Walden inversion. Part XLVIII. The solvolysis of some 3-epimeric 4,4-dimethyl-steroid toluene-*p*-sulphonates. By C. W. Shoppee and G. A. R. Johnston

Iodomercurate complexes with Group V quaternary iodides. Part I. Aqueous decompositions and absorption spectra. G. B. Deacon and B. O. West

Reduced cyclic compounds. Part XIII. The reaction of 1-1′-acetoxycinylcyclohexene with *p*-benzoquinones containing a methoxycarbonyl group. By M. F. Ansell and G. C. Culling

The gaseous oxidation of isopropyl alcohol. Part II. Influence of the surface on the formation of hydrogen peroxide and other products. By A. R. Burgess and C. F. Cullis

Diffusional band spreading in gas-chromatographic columns. Part II. The elution of sorbed vapours. By J. Bohemen and J. H. Purnell

Molecular interaction: molecular polarisation of amines in benzene and carbon tetrachloride. By A. N. Sharpe and S. Walker

Triterpenoids. Part LVIII. The synthesis of isoursenol the ursane analogue of taraxerol. By William Laird, F. S. Spring, and Robert Stevenson

Steroids and Walden inversion. Part XLIX. Further observations on the bromination of 5α-cholestan-4-one. By C. W. Shoppee and Ruth E. Lack

Steric effects in di- and tri-arylmethanes. Part VI. Nucleophilic replacements in triphenylmethane dyes. By C. C. Barker and C. Hallas

Kinetics and mechanism of oxidation of mandelic, dl-malic, and lactic acid by ceric sulphate. By B. Krishna and K. C. Tewari

Sulphates of monosaccharides and derivatives. Part III. Acid hydrolysis. By M. J. Clancy and J. R. Turvey

The synthesis of thyroxine and related compounds. Part XV. The preparation of thyronines from iodonium salts and derivatives of 3,5-disubstituted tyrosines. By A. Dibbo, L. Stephenson, T. Walker, and W. K. Warburton

The synthesis of thyroxine and related compounds. Part XVI. The preparation of 3,5-dichloro-D-thyronine: an unexpected Walden inversion. By W. K. Warburton

The pyrolysis of methyl nitrite. By L. Phillips

The structure of certain polyazaindenes. Part VIII. Tetra-azaindenes derived from the reaction of ethyl β-ethoxy-α-ethoxycarbonylcrotonate with 3-amino-1,2,4-triazoles. By L. A. Williams

Double bonding in chelated metal complexes. By L. E. Orgel

XUM

Gas-phase eliminations. Part II. The pyrolysis of s-butyl chloride and the direction of eliminations from s-butyl compounds. By ALLAN MACCOLL and R. H. STONE

The pyrolysis of divinylmercury and the strength of the C–H bond in ethylene. By A. F. TROTMAN-DICKENSON and G. J. O. VERBEKE

The dissolution of beryllium in aqueous solutions of mineral acids and ammonium fluoride. By C. J. HARDY and D. SCARGILL

A quantitative study of the nitration of benzothiazole. By E. R. WARD and W. H. POESCHE

The activity coefficients of aqueous solutions of choline chloride at 25°. By R. FLEMING

Molecular rearrangements. Part VI. The thermal rearrangement of *N*-methyl-*N*-p-nitrophenylnitramine. By T. J. BARNES and W. J. HICKINBOTTOM

The mechanism of hydrolysis of acid chlorides. Part VII. Alkyl chloroformates. By E. W. GRUNDEN and R. F. HUDSON

Polysaccharides of the Characeae. Part I. Preliminary examination of starch-type polysaccharide from *Nitella translucens*. By D. M. W. ANDERSON and N. J. KING

A convenient alternative synthesis of 5-hydroxytryptamine. By L. BRETHERICK, K. GAIMSTER, and W. R. WRAGG

The chelates formed by tin(II) with certain amino-polycarboxylic acids. By T. D. SMITH

Chemical and spectroscopic evidence for the occurrence of π-character in carbon–boron bonds. By T. D. COYLE, S. L. STAFFORD, and F. G. A. STONE

The infrared absorption of normal and ^{18}O-labelled *N*-methylbenzamide. By S. PINCHAS, DAVID SAMUEL, and MARTA WEISS-BRODAY

Some reactions of **4,4,14α**-trimethyl-5α-cholest-8,24-dien-3α-yl and -3β-yl toluene-*p*-sulphonates. By G. BANCROFT, Y. Y. HADDAD, and G. H. R. SUMMERS

Reactions with asymmetric diarylethylenes. Part VII. A new synthetic route of tetraarylallenes. By WADIE TADROS, ALFY BADIE SAKLA, and ABDUL AZIZ AMIN HELMY

Tetrahedral nickel(II) complexes and the factors determining their formation. Part II. Complexes with dibutylphenylphosphine and butyldiphenylphosphine. By C. R. C. COUSSMAKER, M. HELY HUTCHINSON, J. R. MELLOR, L. E. SUTTON, and L. M. VENANZI

Conjugated cyclic hydrocarbons and their heterocyclic analogues. Part VI. The condensation of azulenes with aliphatic aldehydes in the presence of perchloric acid. By E. C. KIRBY and D. H. REID

Homolytic aromatic substitution. Part XXIV. The *p*-methylphenylation of nitrobenzene and chlorobenzene. By J. K. HAMBLING, D. H. HEY, S. ORMAN, and GARETH H. WILLIAMS

Homolytic aromatic substitution. Part XXV. The determination of the total and partial rate factors for the phenylation of naphthalene. By D. I. DAVIES, D. H. HEY, and GARETH H. WILLIAMS

Homolytic aromatic substitution. Part XXVI. The reactions of some aroyl peroxides with naphthalene. By D. I. DAVIES, D. H. HEY, and GARETH H. WILLIAMS

The stability constants of the silver complexes of some *NN*-substituted 2-hydroxyethylamines. By D. J. ALNER and R. C. LANSBURY

The synthesis and reactions of branched-chain hydrocarbons. Part XIV. The free-radical halogenation of t-butylbenzene. By J. R. B. BOOCOCK and W. J. HICKINBOTTOM

The Raman spectra of bis(trifluoromethylthio)mercury and derived compounds. By A. J. DOWNS, E. A. V. EBSWORTH, and H. J. EMELÉUS

The reactivity of organophosphorus compounds. Part IV. The reaction of carbonyl chloride with some esters. By J. I. G. CADOGAN

The reactivity of organophosphorus compounds. Part V. The reaction of trichloromethyl radicals with trialkyl phosphites. By J. I. G. CADOGAN and W. R. FOSTER

The reactivity of organophosphorus compounds. Part VI. *N*-Chloroamidates. By J. I. G. CADOGAN and W. R. FOSTER

Essential fatty acids. Part I. Synthesis of linoleic, γ-linolenic, arachidonic and docosa-**4,7,10,13,16**-pentaenoic acids. By J. M. OSBOND, P. G. PHILPOTT, and J. C. WICKENS

Crystallographic examination of the α- and β-anomers of D-galactose. By B. SHELDRICK

Leucoanthocyanidins of plants. Part III. Leucopelargonidin from *Eucalyptus calophylla* Kino. By A. K. GANGULY and T. R. SESHADRI

Steric effects in di- and tri-arylmethanes. Part VII. Biphenyl analogues of Crystal Violet and Malachite Green. By C. C. BARKER and A. STAMP

Diphosphine dioxides. Part II. Some diphosphine dioxides with a mono-, di-, and tri-methylene bridge. By GENNADY M. KOSOLAPOFF and ROBERT F. STRUCK

Steric inhibition of hydrogen bonding in solutions of 4-methyl-2,6-di-t-butylphenol. By J. J. WREN and P. M. LENTHEN

Hydrogen bonding in aqueous solutions of maleic acid. By R. E. DODD, R. E. MILLER, and W. F. K. WYNNE-JONES

XUM

Di-*p*-(2-amino-2-carboxyethyl)phenyl peroxide: preparation from tyrosine and probable natural occurrence in proteins. By J. W. Davies and G. Harris

The transmission of polar effects through aromatic systems. Part II. The nitration of benzylic derivatives. By J. R. Knowles and R. O. C. Norman

The ortho : para-ratio in aromatic substitution. Part I. The nitration of methyl phenethyl ether. By R. O. C. Norman and G. K. Radda

The association of n-tetra-alkoxy- and n-alkoxy-chloro-derivatives of titanium. By R. L. Martin and G. Winter

The scope and mechanism of carbohydrate osotriazole formation. Part VI. The apparent dissociation constant of triazole carboxylic acids. By H. El Khadem

Trisethylenediaminenickel(II) thiosulphate as a calibrant for susceptibility measurements by the Gouy method. By N. F. Curtis

Magnetic perturbation of singlet–triplet transitions. Part VI. Octa-1,3,5,7-tetraene. By D. F. Evans

The scope and mechanisms of carbohydrate osotriazole formation. Part V. Chloro- and iodo-phenylosotriazoles. By H. El Khaden, Zaki M. El-Shafei, and M. H. Meshreki

Cyclic diarsines. Part VI. The thermal decomposition of some cyclic quaternary diarsonium dihydroxides and dibromides. By M. H. Forbes, Denys M. Heinekey, Frederick G. Mann, and Ian T. Millar

Pyranoquinolines. Part II. By K. Elliott and E. Tittensor

The preparation of *o*-(4-phenylbuta-1,3-dienyl)phenylboronic anhydride. By P. M. Maitlis

Some experiments based on veratraldehyde. By K. W. Bentley and S. F. Dyke

Reactions of uranium and some uranium compounds with nitrosyl chloride and with liquid nitrosyl chloride–dinitrogen tetroxide mixtures. By C. C. Addison and N. Hodge

The kinetics and mechanisms of aromatic halogen substitution. Part X. Products in the chlorination of biphenyl in acetic acid. By G. H. Beaven, P. B. D. de la Mare, M. Hassan, N. V. Klassen, and E. A. Johnson

Sulphitobis(ethylenediamine)cobalt(III) complexes. By M. E. Baldwin

The stereochemistry of molecules containing the C=C=N group. Part III. The crystal and molecular structure of *N*-ethyl-2,2′-dimethylsulphonylvinylideneamine. By J. J. Daly

The preparation and some reactions of 4-formyl-1-phenylpyrazoles. By I. L. Finar and M. Manning

Substitution patterns of mono-substituted benzene derivatives. By W. Gerrard, E. F. Mooney, and H. A. Willis

A new cinnoline synthesis. Part I. Cyclisation of mesoxalyl chloride phenylhydrazones to substituted 4-hydroxycinnoline-3-carboxylic acids. By J. J. Barber, K. Washbourn, W. R. Wragg, and (in part) E. Lunt

Synthesis of 7-fluoroflavone and related compounds. By F. C. Chen and C. T. Chang

The rearrangement of 1-hydroxyalkylphosphines to alkylphosphine oxides. By S. Trippett

The preparation of complex fluorides by use of sulphur tetrafluoride as fluorinating agent. By R. D. W. Kemmitt and D. W. A. Sharp

Derivatives of *NN*-dialkyldiselenocarbamic acids. By D. Parnard and D. T. Woodbridge

A coloured maleimide and its cyclization with cysteine. By G. D. Clark-Walker and H. C. Robinson

Substituent effects in fluorene. Part III. Hydrolysis of 9-chloro-9-phenylfluorenes. By C. Eaborn, R. C. Golesworth, and M. N. Lilly

Conductimetric titration of sodium in liquid ammonia with phosphine, arsine, stibine, and garmanes. By H. J. Emeléus and K. M. Mackay

The $PtCl_6^{2-}$-I^- and $PtBr_6^{2-}$-I^- replacement reactions. By A. J. Pöe and M. S. Vaidya

The reaction of uranium with solutions of alkylammonium nitrates in dinitrogen tetroxide; some properties of alkylammonium uranyl nitrates. By C. C. Addison and N. Hodge

The Mannich reaction with cholesta-1,4-dien-3-one. By G. I. Gregory and A. G. Long

The heat of autoprotolysis of sulphuric acid. By B. Dacre and P. A. H. Wyatt

Alicyclic alkoxyl radicals in the thermal decomposition of cyclohexyl- and 1-methyl-cyclohexyl nitrites. By Peter Gray, P. Rathbone, and A. Williams

Thermochemical studies. Part IV. Heats and entropies of reaction of transition metal ions with diethylenetriamine. By M. Ciampolini, P. Paoletti, and L. Sacconi

Structure and reactivity of the oxyanions of transition metals. Part XI. Ultraviolet spectra of monosubstituted chromate ions. By U. Klaning and M. C. R. Symons

The cross-linking of cellulose and its derivatives. Part II. Preparation of some new amino-derivatives of D-glucose and of D-galactose. By W. M. Corbett

The cross-linking of cellulose and its derivatives. Part III. The addition of amines to crotonyl esters. By W. M. Corbett and J. E. McKay

XUM

Transition-metal fluorocarbon complexes. Part I. Derivatives of perfluoro-olefins. By H. H. Hoehn, L. Pratt, K. F. Watterson, and G. Wilkinson

Scymnol sulphate and anhydroscymnol. By A. D. Cross

Hydrolysis of *N*-acylphosphoramidic acids. Part IV. *N*-Benzenesulphonylphosphoramidic acid. By M. Halmann, A. Lapidot, and David Samuel

The alkaloids of the amaryllidaceae. Part IX. Racemisation of buphanitine (nerbowdine) during Oppenauer oxidations. By A. Goosen, E. V. O. John, F. L. Warren, and K. C. Yates

The synthesis of thyroxine and related compounds. Part XVII. The preparation of some additional compounds related to thyroxine. By A. Dibbo, J. C. P. Sly, L. Stephenson, T. Walker, W. K. Warburton, and K. D. E. Whiting

A simple synthesis of α,β-dialkylacrylic acids. By Israel Shahak

α-1,4-Glucosans. Part XII. End-group assay of glycogens by oxidation with sodium metaperiodate. By D. J. Manners and A. Wright

Picrotoxin and tutin. Part XI. By G. F. Browne, R. B. Johns, and K. R. Markham

Picrotoxin and tutin. Part XII. The structure of tutin. By R. B. Johns and K. R. Markham

Constituents of vitex agnus castus seeds. Part I. Casticin. By I. Belic, J. Bergant-Dolar, and R. A. Morton

Degradative studies of peptides and proteins. Part VI. The cyclisation and degradation of *N*-phenylthiocarbamoylsarcosine derivatives. By D. T. Elmore

π-Cyclopentadienyl- and cyclopentadiene-iron carbonyl complexes. By A. Davison, M. L. H. Green, and G. Wilkinson

Azasteroids. Part II. 3-Aza- and 4-aza-A-homo-5α- and -5β-androstanes, and the structure of neosaman. By C. W. Shoppee and G. Krueger

Polysaccharides from the green seaweeds of *Caulerpa* spp. Part III. Detailed study of the water-soluble polysaccharides of *C. filiformis*. Comparison with the polysaccharides synthesised by *C. racemosa* and *C. sertularioides*. By I. M. Mackie and Elizabeth Percival

Reactions of fluorocarbon radicals. Part XVI. Photolysis of some perhalogeno-acetones. By R. N. Haszeldine and F. Nyman

Mechanism of reactions in the sugar series. Part IV. The structure of the carbonium ions formed in the acid-catalysed solvolysis of glucopyranosides. By B. E. C. Banks, Y. Meinwald, A. J. Rhind-Tutt, I. Sheft, and C. A. Vernon

Modified steroid hormones. Part XXII. 6α,16α-Dimethylprogesterone and 17α-acetoxy-6α-methyl-16-methyleneprogesterone. By D. N. Kirk, V. Petrow, and D. M. Williamson

The infrared absorption of normal and ^{18}O-labelled *NN*-dimethylbenzamide. By S. Pinchas, David Samuel, and Marta Weiss-Broday

Organic fluorine compounds. Part XXVII. Synthesis of α-fluoro-β-alanine. By Ernst D. Bergmann and Sasson Cohen

Carbonate derivatives of methyl α-D-mannopyranoside and of D-mannose. By L. Hough and J. E. Priddle

The infrared spectra of some transition metal perchlorates. By B. J. Hathaway and A. E. Underhill

Potential anti-purines. Part IV. The synthesis of 9-dimethylaminopurines. By C. L. Leese and G. M. Timmis

1-Aminoimidazoles and derivatives. Part I. The synthesis of 1-amino-derivatives of 5-amino-2-methylimidazole-4-carboxamide. By C. L. Leese and G. M. Timmis

Chemistry of micrococcin P. Part V. The infrared absorption spectra of thiazoles. By (Mrs.) M. P. V. Mijović and James Walker

Chemistry of micrococcin P. Part VI. Racemisation of 2-(1-amino-2-methylpropyl)thiazole-4-carboxylic acid, and related studies. By (Mrs.) B. M. Dean, (Mrs.) M. P. V. Mijović, and James Walker

Arsinophosphonium salts. By J. M. F. Braddock and G. E. Coates

Benzocyclobutenes. Part I. Attempted syntheses of 1,2-diphenylbenzocyclobutene. By Wilson Baker, J. F. W. McOmie, G. A. Pope, and (in part) D. R. Preston

Benzocyclobutenes. Part II. A new synthesis of benzocyclobutene and of 1,2-diphenylbenzylbenzocyclobutene. By Wilson Baker, J. F. W. McOmie, and D. R. Preston

The orientation of some bromo-1-phenylpyrazoles. By I. L. Finar and D. B. Miller

Condensed ions in aqueous solutions. Part II. Compounds of quinquevalent vanadium with orthophosphate. By R. U. Russell, and J. E. Salmon, and (in part) H. R. Tietze

The proton magnetic resonance spectra of porphyrins. Part I. The effect of β-substitution on the proton chemical shifts of porphyrins. By R. J. Abraham, A. H. Jackson, and G. W. Kenner

XUM

Pteridine studies. Part XIV. The methylation of 2-amino-4-hydroxypteridine and related compounds. By D. J. Brown and N. W. Jacobsen
The synthesis of totarolone methyl ether. By D. A. H. Taylor
Hydroxylation of 5α,6β-dibromo-cholestan-3β-yl acetate by chromic acid. By A. L. J. Beckwith
Studies in relation to biosynthesis. Part XXIV. Some remarks on the structure of echinulin. By A. J. Birch, C. E. Blance, S. David, and Herchel Smith
Studies in the synthesis of terpenes. Part VI. Some reactions of 3-methylbutane-1,3-diol. By T. G. Halsall and A. R. Hands
The formation of aromatic hydrocarbons at high temperatures. Part XII. The pyrolysis of benzene. By G. M. Badger and J. Novotny
The formation of aromatic hydrocarbons at high temperatures. Part XIII. The pyrolysis of 3-vinylcyclohexene. By G. M. Badger and J. Novotny
The formation of aromatic hydrocarbons at high temperatures. Part XIV. The pyrolysis of [α-^{14}C]ethylbenzene. By G. M. Badger and R. W. L. Kimber
The reaction of dialkyl phosphites and trialkyl phosphates with sodium *NN*-diethyl dithiocarbamate. By T. D. Smith
An aldobiouronic acid isolated from *Fagara xanthoxyloides* gum. By F. G. Torto
The reaction of cyanogen chloride with sodium salts of carboxylic acids. By J. A. Barltrop, A. C. Day, and (in part) D. B. Bigley
Gibberellin A_2. By John Frederick Grove
The magnetic properties of some d^3 complexes. By B. N. Figgis, J. Lewis, and F. E. Mabbs
The magnetic properties of some d^4 complexes. By A. Earnshaw, B. N. Figgis, and J. Lewis

XUM

XUM

358. *Gallotannins. Part I. Introduction: and the Fractionation of Tannase.*[1]

By E. Haslam, R. D. Haworth, K. Jones, and H. J. Rogers.

Earlier work on the chemistry of the gallotannins is summarised and a description is given of the separation of the enzyme tannase into fractions with specific properties. In particular a galloyl esterase, valuable in the investigation of the gallotannins, has been isolated, which lacks significant carbohydrase activity but hydrolyses galloyl esters to gallic acid and the corresponding alcohol.

The vegetable tannins are usually classified into (1) the condensed or non-hydrolysable tannins, including extracts of Quebracho (*Schinopsis lorentzii* or *balansae*) and wattle (*Acacia mollissima*), which contain little if any carbohydrate material and are converted into insoluble, amorphous phlobaphenes by the action of mineral acids, and (2) the hydrolysable tannins which yield carbohydrates, usually glucose, and one or more phenolic acids by reaction with acids, alkalis, or enzymes.

The hydrolysable tannins are subdivided into (2a) the gallotannins, including Turkish (*Quercus infectoria*, galls) and Chinese (*Rhus semialata*, galls) gallotannins and sumach tannins (*Rhus coriaria* and *typhina*), yielding glucose and phenolic acids of which gallic acid predominates on hydrolysis; and (2b) the ellagitannins, including myrobalans (*Terminilia chebula*), algarobilla (*Caesalpinia brevifolia*), divi-divi (*Caesalpinia coriaria*), and valonea (*Quercus valonea*) extracts, which give, on hydrolysis, glucose and ellagic acid together with gallic acid and frequently with other acids structurally related to gallic acid. This division of the hydrolysable tannins is not entirely satisfactory. Chebulinic acid,[2] a crystalline constituent of myrobalans, is usually included in the gallotannin group, although it has close structural relations with the ellagitannins, and the main component of Tara tannin (*Caesalpinia spinosa*) (see Part III of this series) yields quinic and gallic acid, but no glucose on hydrolysis.

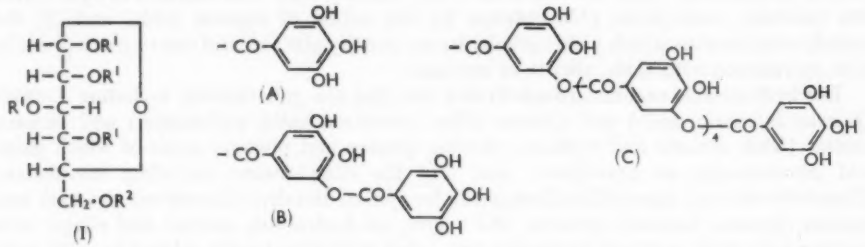
The non-hydrolysable tannins are complex products of unknown constitution which probably result from the condensation [3] and/or the oxidation [4] of flavanoid compounds such as catechin or the leucoanthocyanins, although the work of Grassmann, Endres, and Pauchner [5] on the tannin of spruce bark suggests that other structural units may be involved. Remarkable advances have been made in recent years in ellagitannin chemistry, particularly by Schmidt and his colleagues [6] at Heidelberg, who have suggested attractive formulæ for corilagin and chebulagic acid (from myrabalans and divi-divi), and brevifolincarboxylic acid and brevilagin (from algarobilla).

The chemistry of the gallotannins, which is the main concern of this and subsequent papers, formed the subject of the classical work of Emil Fischer.[7] As a result of (*a*) analytical work including the amounts of glucose and gallic acid liberated by hydrolysis, and (*b*) the yields of 3,4-di-*O*-methyl- and 3,4,5-tri-*O*-methyl-gallic acid obtained by hydrolysis of the methylated tannin, Fischer [7] and Freudenberg [8] concluded that the amorphous Chinese gallotannin was a mixture of isomers and closely related compounds whose average composition corresponded to that of a β-penta-*m*-digalloylglucose (I; $R^1 = R^2 = B$).

[1] For a preliminary account see Haworth, Jones, and Rogers, *Proc. Chem. Soc.*, 1958, 8.
[2] Fischer and Freudenberg, *Ber.*, 1912, **45**, 915; Fischer and Bergmann, *Ber.*, 1918, **51**, 298; Freudenberg, *Ber.*, 1919, **52**, 1238; Freudenberg and Fick, *Ber.*, 1920, **53**, 1728; Freudenberg, *Annalen*, 1927, **452**, 303; Schmidt, *Fortschr. Chem. org. Naturstoffe*, 1956, 72.
[3] Freudenberg and Weinges, *Annalen*, 1954, **590**, 140.
[4] Hathway and Seakins, *J.*, 1957, 1562; *Biochem. J.*, 1957, **65**, 32P; 1957, **67**, 239.
[5] Grassmann, Endres, and Pauckner, *Ber.*, 1958, **91**, 136, 141.
[6] Schmidt, ref. 2; *Z. Naturforsch.*, 1957, **12**, 262.
[7] Fischer, *Ber.*, 1913, **46**, 3253; 1919, **52**, 809.
[8] Freudenberg, "Tannin, Cellulose, and Lignin," Verlag Chemie, Berlin, 1933, p. 38.

XUM

Comparison of Chinese gallotannin with the amorphous synthetic β-penta-*m*-digalloylglucose [9] revealed very many similarities, although differences in water solubility and optical rotatory values were recorded. Karrer, Salomon, and Payer [10] separated Chinese gallotannin by precipitation with aluminium hydroxide into fractions of varying optical rotatory values, which yielded, on treatment with acetic acid and hydrobromic acid, varying amounts of tetra-*O*-galloylglucosyl bromide, thus supporting the basic structure advanced by Fischer. The latter, however, envisaged the possibility of the presence of tri- or even tetra-galloyl chains in the tannin, and Freudenberg [11] emphasised the complexity of the problem by pointing out that many arrangements, varying from penta-*m*-digalloylglucose to a compound (I) where $R^1 = A$ and $R^2 = C$, were consistent with the experimental observations. The claim by Nierenstein and his colleagues [12] to have isolated tetra-*O*-methylglucose by hydrolysis of diazomethane-methylated tannin has been adequately criticised,[13] but the absence of alcoholic hydroxyl groups has never been convincingly established.



Similar analyses of Turkish gallotannin by Fischer and Freudenberg [14] indicated an average composition of a β-pentagalloylglucose (I; $R^1 = R^2 = A$), and the amorphous tannin displayed many similarities to the synthetic product.[9] The isolation, however, of small amounts of 3,4-di-*O*-methylgallic acid from hydrolysis of the methylated tannin showed that some of the gallic acid was linked in the form of a depside, and Freudenberg [8] concluded that, on average, one of the five glucose hydroxyl groups is free, one is esterified with *m*-digallic acid, and the remaining three with gallic acid. Karrer, Widmer, and Staub [15] separated Turkish gallotannin by precipitation with aluminium hydroxide into fractions with varying optical rotatory values, and like Fischer and Freudenberg [14] they reported the presence of significant amounts of ellagic acid in Turkish gallotannin.

More recent work, usually involving chromatographic methods, has revealed certain anomalies with earlier results. Thus Asquith [16] has shown by paper-chromatographic techniques that synthetic β-pentagalloylglucose, prepared by Fischer's method, is impure, and White,[17] although confirming the presence of appreciable amounts of ellagic acid in Turkish gallotannin, states that pentagalloylglucose "is of little if any significance" in the extract. Kirby, Knowles, and White,[18] and White,[17] have demonstrated that Fischer's Chinese gallotannin was contaminated with gallic and *m*-digallic acid, and traces of two other compounds which they considered were pentagalloylglucose and a trigallic acid respectively. The main gallotannin constituent, isolated by ethyl acetate

[9] Fischer and Bergmann, *Ber.*, 1918, **51**, 1760.
[10] Karrer, Salomon, and Payer, *Helv. Chim. Acta*, 1923, **6**, 17.
[11] Freudenberg, "Die Chemie der naturlichen Gerbstoffe," Verlag Chemie, Berlin, 1920, p. 101.
[12] Nierenstein, Spiers, and Geake, *J.*, 1921, **119**, 284.
[13] Schmidt, *Annalen*, 1934, **479**, 1.
[14] Fischer and Freudenberg, *Ber.*, 1912, **45**, 915, 2709; 1914, **47**, 2485.
[15] Karrer, Widmer, and Staub, *Annalen*, 1923, **433**, 288.
[16] Asquith, *Nature*, 1951, **168**, 738—739.
[17] White, "The Chemistry of the Vegetable Tannins," Society of Leather Trades' Chemists, Croydon, 1956, p. 13.
[18] Kirby, Knowles, and White, *J. Soc. Leather Trades' Chemists*, 1951, **35**, 338; 1952, **36**, 148.

from an aqueous-alcoholic extract buffered to pH 6·5 by means of sodium hydrogen carbonate, was an amorphous powder giving analytical results inconsistent with Fischer's formulation. As a result of new methods of analysis it was claimed that (1) gallotannin contained 4—5 galloyl groups per hexose molecule, (2) hydrolysis of the methylated product, which still contained acetylable hydroxyl groups, gave a high yield of 3,4,5-tri-*O*-methylgallic acid but very little 3,4-di-*O*-methylgallic acid, and (3) the chromatographic evidence and the analytical results suggested a trisaccharide and not a glucose core. The suggested polygalloylated trisaccharide structure,[17] which is quite inconsistent with our results, was subsequently withdrawn by King and White.[19]

Lowe [20] suggested that Sicilian sumach (*Rhus coriaria*) extract was identical with Chinese gallotannin, but Karrer, Widmer, and Staub [15] suggested a close resemblance with Turkish gallotannin. Catravas and Kirby [21] later showed that two-way paper chromatograms of Sicilian sumach and Chinese gallotannin were indistinguishable, but claimed that the tannin contained 16·8—17·7% of glucose instead of the 4—8% reported by the earlier workers. More recently Grassmann, Stiefenhofer, and Endres [22] have claimed that the tannin of Stagshorn sumach (*Rhus typhina*) is a polygalloylated tetrasaccharide, composed of arabinose, rhamnose, and two molecules of glucose, but again the claims are quite inconsistent with the results reported in the present series of papers.

This brief review indicates that further work is necessary, and that the following are some (but by no means all) points which require attention: (1) the homogeneity of the gallotannins, (2) the nature of the carbohydrate core, (3) the presence of polygalloyl chains, (4) the extent of esterification of the carbohydrate core.

In this paper an attempt has been made to develop a method which would differentiate between the conflicting views of Fischer,[7] White,[17] and Grassmann *et al.*[22] on the nature of the carbohydrate nuclei in the gallotannins and in the sumach tannins. It is agreed by all that the ultimate products of hydrolysis by acids and by the enzyme tannase are gallic acid and glucose, but White [17] and Grassmann *et al.*[22] claim that intermediate polysaccharides are produced by hydrolysis with alkali. The enzyme tannase, which has been frequently used in the analysis of tannins, is produced by the growth of *Aspergillus niger* on solutions of commercial myrobalans [23] or gallotannin.[24] This mould is known to contain specific carbohydrases and we have investigated these activities in tannase, although the main objective behind these experiments was the separation, if possible, of specific galloyl esterases from the carbohydrases of the enzyme.

It has been shown that a specific maltase active against maltose but not against methyl α-glucoside,[25] a trehalase active against trehalose,[26] and β-glucosidases active against cellobiose and salicin,[27] were present in tannase, but the presence of previously reported β-rhamnosidase,[28] activive against quercetrin, was not confirmed. Some, though not all, preparations of tannase hydrolysed melibiose, turanose, starch, and inulin. The hydrolysis of sucrose by tannase was shown to be due to a β-fructoinvertase and not to the alternative α-glucoinvertase, since raffinose was readily degraded to glucose, galactose, and melibiose whereas melizitose gave only traces of glucose with the enzyme. Tannase also hydrolysed methyl gallate, protocatechuate, and 3,5-dihydroxybenzoate, but not methyl salicylate, 2,4-dihydroxybenzoate, or 2,5-dihydroxybenzoate, and these results are in agreement with the previous observations by Dyckerhoff and Armbruster.[29] The finding of these authors

[19] King and White, *Chem. and Ind.*, 1958, 683.
[20] Löwe, *Z. analyt. Chem.*, 1873, **12**, 128.
[21] Catravas and Kirby, *J. Soc. Leather Trades' Chemists*, 1948, **32**, 155.
[22] Grassmann, Stiefenhofer, and Endres, *Chem. Ber.*, 1956, **89**, 454.
[23] Freudenberg, Blümmel, and Frank, *Z. physiol. Chem.*, 1927, **164**, 262.
[24] Knudsen, *J. Biol. Chem.*, 1913, **14**, 159.
[25] Bourquelot, *Compt. rend.*, 1883, **97**, 1322.
[26] Bourquelot, *Compt. rend.*, 1893, **116**, 826.
[27] Hofmann, *Biochem. Z.*, 1934—1935, **275**, 320.
[28] Freudenberg and Walpulski, *Ber.*, 1921, **54**, 1659.
[29] Dyckerhoff and Armbruster, *Z. physiol. Chem.*, 1933, **219**, 38.

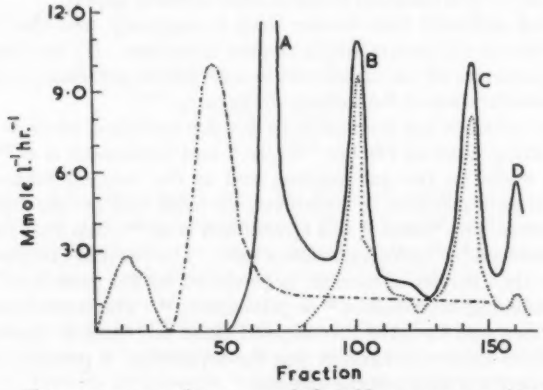
XUM

that methyl *m*- and *p*-hydroxybenzoate, and ethyl and phenyl acetate, acted as substrates for tannase was, however, not confirmed.

Quantitative measurements of the β-glucosidase activity were made by using salicin,[30] of the β-fructoinvertase by using sucrose,[31] of the maltase by estimation of the glucose after hydrolysis of maltose, and of the galloyl esterase by hydrolysis of methyl gallate by a modification of the method described by Schmidt.[32] The hydrolysis of methyl gallate was shown to follow zero-order kinetics, whereas Dyckerhoff and Armbruster [29] report the reaction to be of first-order; but these authors used long reaction times during which the liberated gallic acid might inhibit the enzyme or cause an alteration in the buffer pH. The pH optimum of the galloyl esterase, however, lay in the range 5·0—6·5 as recorded by these workers.[29]

Preliminary attempts at the fractionation of tannase were made by heat treatment, by the action of cupric and mercuric ions, and by precipitation with ammonium sulphate. Some denaturation of the carbohydrases was observed on heating and the invertase was inhibited by mercuric ions in concentrations greater than 10^{-5}M, but no separation was

Fractional elution of tannase ingredients.



—— *Esterase*; – – – *maltase*; . . . *β-glucosidase*; – · – · – *invertase*

observed with ammonium sulphate. Column electrophoresis [33] gave a partial separation and also indicated that the enzymes were acidic proteins having isoelectric points below 5, but the methods were not of practical value in separation of the esterases from the carbohydrases of the enzyme.

Separation of the galloyl esterase was eventually achieved by ion-exchange chromatography on the basic resin Dowex "2," gradient elution with a buffer of decreasing pH being used. Qualitative tests on the substrates mentioned above showed that the maltase was eluted initially, followed by the invertase and the esterase, but much of the latter was overlapped by β-glucosidases. No melibiase was detected in the eluate, although the starting material was active. Quantitative determinations of the enzyme activities gave the more complete picture illustrated in the Figure. Attempts to correlate the enzymic activities with the protein content of the eluates were unsuccessful and this may be due to the presence of much inert protein in the original tannase.

The galloyl esterase was eluted in four peaks (A,B,C,D), three (B,C,D) of which were

[30] Bray, Thorpe, and White, *Biochem. J.*, 1950, **46**, 275.
[31] Park and Johnson, *J. Biol. Chem.*, 1949, **181**, 150.
[32] Schmidt, "Die Methoden der Fermentforschung," Georg. Thieme, Leipzig, 1941.
[33] Fonss-Beck and Li, *J. Biol. Chem.*, 1954, **207**, 175.

largely contaminated with the β-glucosidase. The main esterase peak (A) was inactive towards salicin, maltose, raffinose, melizitose, nigerose, isomaltose, gentiobiose, and maltotetrose, but showed a slight activity towards sucrose which was obviously due to the tailing of the invertase peak. Attempts to free the esterase (A) from the small invertase activity were made by further chromatography of the esterase and by chromatography of tannase which had undergone preliminary purification by precipitation of inert material at pH 9·0 and autolysis at pH 5·0; both these methods, however, resulted in the loss of esterase activity.

Consequently we have used the component corresponding to the main specific galloyl esterase peak (A) to investigate the nature of the carbohydrate core of Chinese and Turkish gallotannins, Sicilian and Stagshorn sumach and of other tannins. As this specific galloyl esterase lacks significant carbohydrase activities, it would be expected to hydrolyse the tannins to gallic acid and the carbohydrate core. It is important to appreciate that the small residual invertase activity will not invalidate in any way the conclusions derived from the action of the enzyme on the tannin, since earlier work [7] and the more recent chromatographic evidence of Grassmann, Stiefenhofer, and Endres [22] and ourselves has demonstrated that the tannins investigated do not contain fructose. The detailed results of the action of this esterase on the gallotannins are described in later papers, but in all cases examined the products of hydrolysis were glucose and gallic acid. No indication of other carbohydrates was detected and it is concluded that Turkish and Chinese gallotannins, and Sicilian and Stagshorn sumach tannins, are galloylated glucoses, as suggested originally by Fischer,[7] and not galloylated polysaccharides, as suggested by later workers.[17,22]

Experimental

Preparation of Tannase.—A sample of *Aspergillus niger* " 106 " was kindly supplied by Professor S. R. Elsden and used throughout this work. The mould was grown on the 2% tannic acid solution described by Knudsen [24] adjusted to pH 6·5 with 2N-sodium hydroxide. Incubation was carried out at 30° for 6 days, then the mycelium was collected and converted into the " acetone powder." The latter (48 g.) was extracted by shaking with 0·2% sodium chloride solution (1 l.) at 2° for 24 hr. and the mixture was then filtered through a pad of Hyflo-supercel to give a clear brown solution. The latter was dialysed for 18 hr. at 2° against 0·001N-acetate buffer (pH 5·0) and after freeze-drying gave tannase (0·970 g.).

Enzymic Activities of Tannase.—(1) *Qualitative methods.* (*a*) Carbohydrases. Sucrose, cellobiose, maltose, lactose, raffinose, melibiose, turanose, trehalose, salicin, methyl α-glucoside, and starch were used as 0·5% solutions in 0·1N-acetate buffer (pH 5·0). Inulin was used as a saturated solution in the same buffer, and quercetrin as a saturated solution containing 10% ethanol. The substrates (0·5 c.c.) were incubated overnight at 37° with 0·1% tannase solution (0·1 c.c.), and the hydrolysis products identified by paper chromatography on Whatman No. 1 paper in the solvent system butan-2-ol–acetic acid–water (14 : 1 : 5) with known carbohydrates as markers. The sugars were detected by spraying with aniline hydrogen phthalate [34] or silver nitrate.[35] The results are discussed on p. 1831.

(*b*) Esterase. The substrates were tested as 0·5% solutions in 0·1N-acetate buffer (pH 5·0; 0·5 c.c.) and incubated overnight with 0·1% tannase solution in 0·1N-acetate buffer (pH 5·0; 0·1 c.c.). The solutions were chromatographed on Whatman No. 1 paper in 6% acetic acid, and the products identified with markers. *ortho*- and *para*-Dihydric phenols were detected with a ferric chloride–potassium ferricyanide [36] spray, and other phenols with a spray of diazotised sulphanilic acid.[37] The results are discussed on p. 1831.

Ethyl and phenyl acetate were used as 0·1% solutions in aqueous acetone (5%) adjusted to pH 5 with 0·1N-sodium hydroxide. 0·1% Tannase solution (0·1 c.c.) was added and the reaction followed on an autotitrator. No alkali was consumed for 1 hr.

[34] Hough, *J.*, 1950, 1702.
[35] Trevelyan, Porter, and Harrison, *Nature*, 1950, **166**, 144.
[36] Kirby, Knowles, and White, *J. Soc. Leather Trades' Chemists*, 1953, **37**, 283.
[37] Ames and Mitchell, *J. Amer. Chem. Soc.*, 1952, **74**, 252.

(2) *Qualitative methods.* The unit of enzyme activity was defined as 1 litre of enzyme solution which in 1 hr. at 37° will hydrolyse 1 millimole of substrate.

(*a*) Invertase. 0·1% Tannase solution (1·0 c.c.) was incubated at 37° with sucrose solution (3·0 c.c.; $1{\cdot}33 \times 10^{-2}$M) in 0·1N-acetate buffer (pH 5·0). Samples were withdrawn every 10 min. and the glucose was determined by the method of Park and Johnson.[31]

(*b*) β-Glucosidase. 0·1% Tannase (1·0 c.c.) was incubated at 37° with salicin solution (3·0 c.c.; $1{\cdot}3 \times 10^{-2}$M) in 0·1N-acetate buffer (pH 5·0). Samples were withdrawn every 10 min. and analysed for saligenin by the Folin reagent.[30]

(*c*) Maltase. An approximate measure of maltase activity was obtained by incubation of 0·1% tannase solution (0·25 c.c.) with maltose solution ($1{\cdot}3 \times 10^{-2}$M) in 0·01N-acetate buffer (pH 5·0; 0·75 c.c.). Samples (0·01 c.c.) were chromatographed on Whatman No. 1 paper together with standard glucose solutions in butan-2-ol–acetic acid–water (14 : 1 : 5); the glucose spots on the chromatograms were cut out and eluted with water (4·0 c.c.) for 4 hr. After filtration, aliquot parts (3·0 c.c.) were estimated for glucose.[31]

(*d*) Galloyl esterase. 0·5% Methyl gallate solution (0·9 c.c.) was adjusted to pH 5·0 with 0·01N-sodium hydroxide, and 0·1% tannase solution (0·1 c.c.) was added. The reaction was followed by titration of the liberated gallic acid with 0·01N-sodium hydroxide to pH 6·80 on an autotitrator. The consumption of alkali was 0·15, 0·29, 0·44 c.c. after 10, 20, and 30 min. respectively.

pH *Optimum of Galloyl Esterase.*—The activity of the galloyl esterase was determined at pH 4·0, 5·0, 5·5, 6·0, 6·5, and 7·0, the following values of enzymic activity being obtained: 33, 33·5, 43, 52, 52·5, 53, and 49 respectively. The enzymic activities determined in the presence of a 0·1-molar ratio of free gallic acid at pH 4·5, 5·0, 5·5, 6·0, and 6·5 were 21, 37, 42, 47, and 46 respectively.

Fractionation of Tannase.—(a) *Action of heat on tannase.* A 0·1% solution of tannase (2 c.c.) was heated from 30° to 100° during 45 min. and, after dilution to 5 c.c., samples (0·2 c.c.) were tested for activity against methyl gallate, sucrose, and salicin. Comparison with an identical unheated solution showed that the invertase and β-glucosidase activities had been reduced. The esterase was unaffected.

(b) *Action of cupric and mercuric ions on tannase.* To samples of the substrate (sucrose, salicin, or methyl gallate) in 0·1N-acetate buffer (pH 5·0; 0·8 c.c.) were added portions (0·1 c.c.) of cupric sulphate or mercuric chloride solution so as to give final concentrations of these ions in the range 10^{-3}—10^{-6}M. 0·1% Tannase solution (0·1 c.c.) was added to each and the solutions were incubated for 12 hr. at 37°. Solutions were similarly prepared for comparison containing tannase and substrate, and tannase and metal ions. Examination by paper chromatography showed that mercuric ions in excess of 10^{-4}M inactivated the invertase. No effect was observed with the cupric ions.

(c) *Column electrophoresis of tannase.* The apparatus used was similar to that used by Fonss-Beck and Li.[33] Starch was packed as a slurry with the appropriate buffer solution (0·1N-acetate for pH 5·0; 0·1N-phosphate for pH 7·0 or pH 8·0) in a semicylindrical glass trough (50 × 2·5 cm.). Excess of buffer was drained off a slot cut in the middle of the column, and a piece of Whatmann " 3MM " paper, which had previously been soaked in water (0·1 c.c.) containing tannase (3 mg.), was inserted. The column was covered with liquid paraffin to prevent evaporation, and a current of 18 milliamp. at 230 v passed for 24 hr. at 2°. The liquid paraffin was removed by washing with light petroleum (b. p. 60—80°), and the column cut into 1 cm. sections with a thin-bladed scalpel. Each section was extracted by shaking with 0·1N-acetate buffer (pH 5·0; 5·0 c.c.) for 3 hr. and, after centrifuging, samples were tested for esterase, β-glucosidase, and invertase activity. The tabulated results were obtained

	pH of electrophoresis		
	5·0	7·0	8·0
Esterase	Sections 1—5	Sections 3—9	Sections 3—13
Invertase	,, 1—4	,, 1—5	,, 1—9
β-Glucosidase	,, 3—6	None detected	,, 5—13

(d) *Chromatography of tannase on Dowex " 2 ".* Dowex " 2 " resin (200—400 mesh) was equilibriated with 0·15N-acetate buffer (pH 4·75) and set up as a column (13 × 3·2 cm.). A solution of tannase (66 mg.) in 0·15N-acetate buffer (pH 4·75; 2·0 c.c.) was adsorbed, and

gradient elution carried out at 2° with 0·2N-acetate buffer in the reservoir and a mixing chamber containing 0·15N-acetate buffer (pH 4·75; 400 c.c.). Fractions (9·0 c.c.) were collected at the rate of 2 per hr.; at fraction 110 the buffer solution in the reservoir was replaced by 0·75N-acetic acid (pH 2·50) and a further 57 fractions collected. Every sixth fraction was dialysed at 2° for 18 hr. against distilled water and qualitative tests were carried out with methyl gallate, sucrose, salicin, cellobiose, and melibiose. Quantitative estimations were also made and the protein content determined by the method of Lowry *et al.*[38] Fractions were combined as shown for further study:

Fractions	2—22	32—50	62—81	92—112	139—153	159—165
			A	B	C	D
Enzyme	Maltase	Invertase	Esterase	Esterase	Esterase	Esterase

The combined fractions were concentrated at 25°, dialysed, and freeze-dried, and solutions in 0·01N-acetate buffer (pH 6·0; 4·0 c.c.) were stored at −10°. The esterase fractions were tested for carbohydrase activity by incubating samples (0·1 c.c.) for 48 hr. with 0·5% solutions of sucrose, maltose, nigerose, isomaltose, gentiobiose, and maltotetrose and 1% solutions of raffinose and melizitose in 0·05N-acetate buffer (pH 6·0; 0·5 c.c.). The solutions were prepared for chromatography by passage down a small column of Dowex " 50 " to remove sodium ions, and paper chromatograms were then prepared on Whatman No. 1 paper in butan-2-ol–acetic acid–water (14 : 1 : 5). The first esterase fraction (A) was found to be slightly active against sucrose, and the remaining esterase fractions (B, C, D) were also active against salicin.

(e) *Attempted rechromatography of the esterase fraction A.* A sample of the esterase fraction (A) was rechromatographed on a small column of Dowex " 2 " as described above. The esterase fractions were collected, but on dialysis were rapidly inactivated.

Preliminary Preparation of Tannase.—(a) *Treatment of tannase at* pH 9·0. A 1% solution of tannase (5·0 c.c.) was cooled in ice whilst N-sodium hydroxide was added dropwise until the pH reached 9·0, a heavy precipitate then appearing. This was removed by centrifugation and the supernatant liquid was found to retain all its original activity towards sucrose, salicin, and methyl gallate. After dialysis the tannase was freed from solution by freeze-drying.

(b) *Autolysis of tannase at* pH 5·0. Tannase (24 mg.) which had been subject to treatment at pH 9·0 was dissolved in 0·1N-acetate buffer (pH 5·0; 5·0 c.c.) and incubated under toluene at 37° for 24 hr. After dialysis the material still retained its activity against sucrose, salicin, and methyl gallate, and the two-dimensional chromatograms on Whatman No. 1 paper run in 6% acetic acid and butan-2-ol–acetic acid–water (14 : 1 : 5) did not respond to sprays of silver nitrate [35] or aniline hydrogen phthalate.[34]

Chromatography of Tannase after Treatment at pH 9·0 *and* pH 5·0.—Partially purified tannase (50 mg.) was chromatographed on Dowex " 2 " as described above. The esterase fractions were detected by their activity towards methyl gallate. Concentration at 25° and dialysis, however, rapidly inactivated the esterase.

We thank Imperial Chemical Industries Limited and the Department of Scientific and Industrial Research for grants in aid of the work described in this series of papers; the University of Sheffield for a Henry Ellison Fellowship to H. J. R.; the Department of Scientific and Industrial Research for a Research Scholarship to K. J.; and Professors E. L. Hirst, S. Peat, and M. Stacey for gifts of carbohydrate specimens.

CHEMISTRY DEPARTMENT,
THE UNIVERSITY, SHEFFIELD, 10. [*Received, November 9th*, 1960.]

[38] Lowry, Rosenbrough, and Randall, *J. Biol. Chem.*, 1951, **193**, 265.

XUM

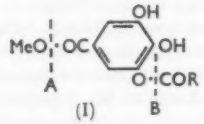
359. *Gallotannins. Part II.* Some Esters and Depsides of Gallic Acid.*

By E. Haslam, R. D. Haworth, S. D. Mills, H. J. Rogers, and (in part) R. Armitage and T. Searle.

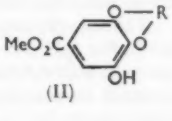
During attempts to distinguish between depside and ester linkages it has been discovered that *o*-hydroxydepsides such as (I) and (III) undergo methanolysis with 90% methanol at pH 5—6, giving in the case of (III) a mixture of methyl protocatechuate and methyl benzoate. The mechanism of the reaction which has applications in gallotannin chemistry is briefly discussed.

A suggestion that *m*-digallic acid was produced as an artefact during the hydrolysis of the gallotannin has been disproved by studies of the hydrolysis of model compounds including digalloyloxyethane, tri-*O*-galloylglycerol, and cyclohexane-*cis*- and -*trans*-1,2-diol digallate.

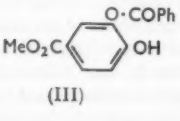
The presence in the gallotannin of *m*-digalloyl and possibly polygalloyl groups has been postulated by previous writers including Fischer,[1] Freudenberg,[2] Karrer,[3] and others. In Part I of this series (preceding paper) the fractionation of the enzyme tannase to give a specific galloyl esterase was described and it was hoped that further fractionation would provide an enzyme with specific reactivity at the depside linkage, *e.g.*, " A " in formula (I), but without effect on the ester aliphatic linkage, *e.g.*, " B " in formula (I). Evidence that two such enzymes exist in tannase was put forward by Toth and Barsony.[4] Such a depsidase would have valuable application in gallotannin chemistry and in order that the fractionation of tannase could be tested model compounds of type (I) have been synthesised.



(I)



(II)



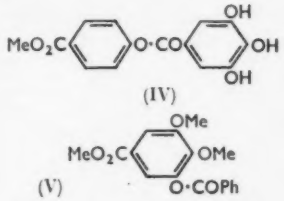
(III)

The preparation of depsides of this type (I) containing methyl gallate residues presented difficulties. Fischer and Freudenberg[5] used the cyclic carbonate (II; R = >CO) and after condensing tri-*O*-methoxycarbonylgalloyl chloride, prepared *m*-digallic acid by hydrolysis of the protecting groups with dilute sodium hydroxide. In a later method[6] methyl 3-*O*-benzoylgallate (I; R = Ph) was prepared by reaction of 3,5-di-*O*-acetylgallic acid and benzoyl chloride, followed by methylation to give the methyl ester of the protected *p*-depside. This was converted into the *m*-depside by alkaline hydrolysis of the acetyl groups and simultaneous rearrangement of the benzoyl group. The latter method has, however, proved unreliable in some cases[7] and we have prepared methyl 3-*O*-benzoylgallate (I; R = Ph) by a modification of the method of Seshadri *et al.*,[8] which uses the preferential acylation at a *meta*- rather than *para*-hydroxyl group relative to a carboxyl group. Methylation of the diester (I; R = Ph) gave methyl 3-benzoyloxy-4,5-dimethoxybenzoate (V); and methyl 3-*O*-benzoylprotocatechuate (III) was prepared

* Part I, preceding paper.

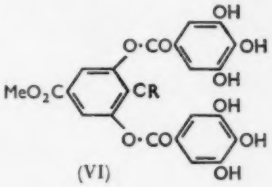
[1] Fischer, *Ber.*, 1919, **52**, 809.
[2] Freudenberg, " Naturliche Gerbstoffe," Verlag Chemie, Berlin, 1920, p. 101.
[3] Karrer, Salomon, and Payer, *Helv. Chim. Acta*, 1923, **6**, 17.
[4] Toth and Barsony, *Enzymologia*, 1943—1945, **11**, 19.
[5] Fischer and Freudenberg, *Ber.*, 1913, **46**, 1116.
[6] Fischer, Bergmann, and Lipschitz, *Ber.*, 1918, **51**, 45.
[7] Cavallito and Buck, *J. Amer. Chem. Soc.*, 1943, **65**, 2141.
[8] Seshadri, Aghoramurtny, and Venkatasubramanian, *Tetrahedron*, 1957, **1**, 310.

similarly by benzoylation of methyl protocatechuate. For the preparation of other depsides a new method was developed, the potentialities of which have, since the completion of this work, been hinted at by Jurd.[9] Methyl gallate was converted into methyl 3,4-diphenylmethylenedioxy-5-hydroxybenzoate (II; R = $>CPh_2$) as described by Robinson, Bradley, and Schwarzenbach;[10] then condensation with tri-*O*-benzylgalloyl chloride[11] followed by hydrogenolysis of the protecting groups from the resultant depside gave methyl *m*-digallate (I; R = 3,4,5-trihydroxyphenyl). A similar method was used to prepare methyl 3-*p*-hydroxybenzoylgallate (I; R = *p*-HO·C_6H_4). Methyl *p*-galloyloxybenzoate (IV) was prepared by condensation of methyl *p*-hydroxybenzoate and tri-*O*-benzylgalloyl chloride and subsequent removal of the protecting groups by hydrogenolysis. Methyl tri-*O*-galloylgallate (VI; R = 3,4,5-trihydroxybenzoyl) and methyl 3,5-di-*O*-galloylgallate (VI; R = H) were prepared by condensation of tri-*O*-benzylgalloyl chloride with methyl gallate and methyl 4-*O*-benzylgallate respectively, followed by hydrogenation to remove protecting groups.

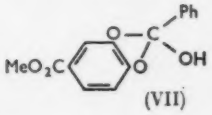


(IV)

(V)



(VI)



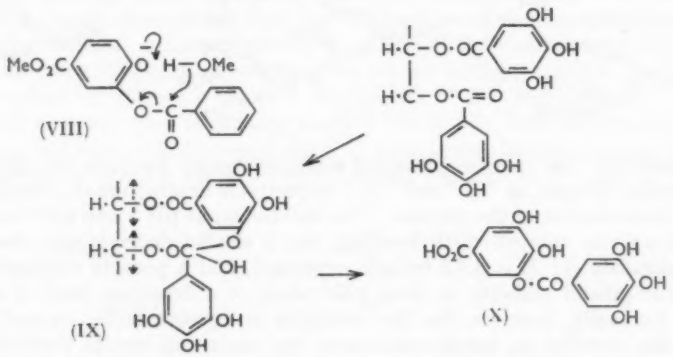
(VII)

The possibility that tannase contained esterases specific for both the aliphatic ester and the depside linkages, as " B " and " A " respectively in structure (I), was investigated by partial denaturation of the enzyme. The incubation at pH 3 and pH 7 considerably reduced its activity towards methyl gallate, but a smaller decrease was observed with methyl *m*-digallate (I; R = 3,4,5-trihydroxyphenyl), and a possible explanation of this would be the greater stability at these pH values of a depsidase than of the normal esterases. Generally, however, the low solubility in aqueous buffer created difficulties in testing the depsides as tannin substrates, but surprising results were obtained by carrying out the reaction in aqueous methanol. When methyl *m*-digallate (I; R = 3,4,5-trihydroxyphenyl) was treated with tannase in 30% methanolic buffer at pH 5—6, methanolysis occurred with the formation of methyl gallate and small amounts of gallic acid. It was shown that rupture of the depside linkage occurred independently of the tannase, and methanolysis of methyl *m*-digallate proceeded smoothly with 90% methanol at 37° at pH 5—6. No methanolysis took place at or below pH 3, and at pH 6 spontaneous hydrolysis occurred. Preliminary experiments indicated that the reaction took place more readily in methanol than ethanol, and in s- or t-butyl alcohol there was no alcoholysis. Examination of other depsides showed that (I; R = Ph or *p*-HO·C_6H_4), (III), and (VI; R = H) underwent methanolysis under similar conditions, the first two giving methyl gallate and methyl benzoate or methyl *p*-hydroxybenzoate respectively, (III) yielding a mixture of methyl protocatechuate and methyl benzoate, and (VI; R = H) giving methyl gallate alone. As the depsides (IV), (V), the *O*-benzoate of (II; R = $>CPh_2$), and methyl trigalloylgallate (VI; R = 3,4,5-trihydroxybenzoyl), and esters such as tri-*O*-galloylglycerol, 1-*O*-galloyl- and β-penta-*O*-galloyl-glucose were stable to the conditions of methanolysis, it was concluded that the reaction requires the presence of an *o*-hydroxydepside grouping, and it is tentatively suggested that the mechanism of the reaction depends on the formation of a cyclic intermediate of the type (VII), which by

[9] Jurd, *J. Amer. Chem. Soc.*, 1959, **82**, 4606.
[10] Robinson, Bradley, and Schwarzenbach, *J.*, 1930, 812.
[11] Clinton and Geissmann, *J. Amer. Chem. Soc.*, 1943, **65**, 85.

analogy with carbinol-amines, such as cotarnine, might be expected to be methylated easily. Alternative mechanisms, such as (VIII), based on the initial ionisation of the hydroxyl group *para* to the methoxycarbonyl group, followed by attack of the methanol, are not so favoured in view of the inability to methanolyse phenyl salicylate. Mechanisms based on activating effects from the methoxylcarbonyl group are unlikely, since mono-*O*-benzoylcatechol was readily methanolysed to methyl benzoate and catechol. The mechanism of the reaction is being investigated more fully, but the methanolysis has obvious applications to gallotannin chemistry, since it brings about the decomposition of depsides of type (I) in a manner for which we had hoped to find an enzyme catalyst. Some of the preliminary results of the reaction with gallotannins are described in Part III of this series.

The presence of *m*-digallic acid (X) in the structure of Chinese gallotannin is based on (*a*) the isolation of 3,4-di-*O*-methylgallic acid and 3,4,5-tri-*O*-methylgallic acid from alkaline hydrolysis of the methylated tannins,[12] (*b*) the detection of *m*-digallic acid (X) (and possibly a trigallic acid) by paper chromatography of the acid and alkaline hydrolysis of gallotannin,[13] and (*c*) the isolation of methyl penta-*O*-methyl-*m*-digallate by methylation of the gallotannin with diazomethane in methanol.[14] It seemed feasible that the *m*-di-



gallic acid might be produced as an artefact during the hydrolysis of the tannin, after intermediate formation of the cyclic derivative (IX) from suitably disposed galloyl groups. Alternatively such structures might exist permanently within the tannin itself. Hydrolysis could then proceed in two ways to give either gallic or *m*-digallic acid and the reaction would be analogous in many ways to that of methanolysis already described.

In order to test this supposition, digalloyloxyethane, tri-*O*-galloylglycerol, and cyclohexane-*cis*- and -*trans*-1,2-diol digallate were prepared by condensing tri-*O*-benzylgalloyl chloride and the appropriate alcohol and then removing the benzyl groups by hydrogenation. Two-dimensional paper chromatography was eminently suited for the detection of intermediate products of the acid and alkaline hydrolysis of these galloyl esters. For example, in the case of tri-*O*-galloylglycerol, after hydrolysis with acids for half an hour, six phenolic substances were then detected; these may be attributed to unchanged tri-*O*-galloyl-, the two isomeric 1,2- and 2,3-di-*O*-galloyl-, the two isomeric 1- and 2-mono-*O*-galloyl-glycerols, and free gallic acid. Similar but less complex patterns were found with other galloylated glycols and all point to the multiplicity of products to be expected from a gallotannin. In all cases, however, acid or alkaline hydrolysis of these galloyl esters gave gallic acid and the corresponding alcohol, no trace of *m*-digallic acid was observed on the paper

[12] Herzig, *Ber.*, 1905, **38**, 989; *Monatsh.*, 1909, **30**, 543.
[13] White, "The Chemistry of the Vegetable Tannins, Society of Leather Trades' Chemists, Croydon, 1956, p. 13.
[14] Herzig, *Ber.*, 1923, **56**, 221.

chromatogram, and there are no grounds for believing that *m*-digallic acid arises as an artefact from gallotannin hydrolysis. The original proposal that di-, tri-, and poly-galloyl chains are present in the tannin structure is thus more consistent with the known facts.

Experimental

Methyl 3-O-*Benzoylgallate* (I; R = Ph).—To a solution of methyl gallate (1·8 g.) in ether (100 c.c.) containing pyridine (2·0 c.c.), benzoyl chloride (1·4 g.) was added. An oil separated and after 6 hr. the ether was decanted, the oil was taken up in ethyl acetate (50 c.c.), and the combined solutions were washed with 2N-hydrochloric acid (50 c.c.), water, sodium hydrogen carbonate solution, and finally water, and dried (Na_2SO_4). Removal of the solvent gave an oil which crystallised on trituration with warm benzene (20 c.c.). Residual methyl gallate was removed in boiling water and crystallisation from ether–light petroleum (b. p. 40—60°) yielded methyl 3-*O*-benzoylgallate (1·1 g.) as prisms, m. p. 172—174° (Fischer, Bergmann, and Lipschitz [6] give m. p. 173—175°) (Found: C, 62·3; H, 4·4. Calc. for $C_{15}H_{12}O_6$: C, 62·5; H, 4·2%). The infrared spectrum, determined on a potassium bromide disc, showed bands at 1718 and 1682 cm.$^{-1}$.

Methyl 3-*Benzoyloxy*-4,5-*dimethoxybenzoate* (V).—An excess of ethereal diazomethane was added to methyl 3-*O*-benzoylgallate (9·0 g.) in ethyl acetate (50 c.c.). After 12 hr. the solution was filtered through a small column of alumina (20 g.) and evaporated; the resultant oil separated from ethyl acetate–light petroleum (b. p. 60—80°) as plates (7·5 g.), m. p. 90° (Fischer, Bergmann, and Lipschitz [6] give m. p. 91—92°).

Methyl p-*Benzyloxybenzoate*.—A solution of methyl *p*-hydroxybenzoate (28 g.) in acetophenone (50 c.c.) and potassium carbonate (28·4 g.) were heated to 150° and benzyl chloride was added with stirring during 1 hr. After a further 7 hours' heating the solvent was removed in steam, and the product collected and crystallised from benzene–light petroleum (b. p. 40—60°); *methyl* p-*benzyloxybenzoate* (31 g.) separated as needles, m. p. 90° (Found: C, 74·2; H, 5·8. $C_{15}H_{14}O_3$ requires C, 74·4; H, 5·8%).

p-*Benzyloxybenzyl Chloride*.—Methyl *p*-benzyloxybenzoate (30·0 g.) was refluxed for 2 hr. in ethanol (100 c.c.) and 10% aqueous sodium hydroxide (800 c.c.). *p*-Benzyloxybenzoic acid (21·0 g.), liberated by acidification, crystallised from ethanol in needles, m. p. 186° (Cavallito and Buck [7] give m. p. 188°). The *chloride* prepared by refluxing the acid (21·0 g.) for 1 hr. with thionyl chloride (25 c.c.) separated from benzene–light petroleum (b. p. 40—60°) in prisms (19·0 g.), m. p. 102° (Found: C, 68·2; H, 4·6. $C_{14}H_{11}ClO_2$ requires C, 68·2; H, 4·4%).

Methyl 3-p-*Benzyloxybenzoyl*-4,5-*diphenylmethylenedioxybenzoate*.—*p*-Benzyloxybenzoyl chloride (2·75 g.) and methyl 3,4-diphenylmethylenedioxy-5-hydroxybenzoate (II; R = $>CPh_2$) (3·5 g.) were dissolved in chloroform (100 c.c.) containing pyridine (4·0 c.c.). After 48 hr. the solution was washed successively with dilute hydrochloric acid, sodium hydroxide, and water, dried, and evaporated under reduced pressure. The product separated from benzene–light petroleum (b. p. 40—60°) in prisms (4·5 g.), m. p. 168° (Found: C, 75·3; H, 4·8. $C_{35}H_{26}O_7$ repuires C, 75·1; H, 4·7%).

Methyl 3-*Benzoyl*-4,5-*diphenylmethylenedioxybenzoate*.—Prepared as above, this *ester* crystallised from methanol in plates, m. p. 113—114° (Found: C, 74·1; H, 4·7. $C_{28}H_{20}O_6$ requires C, 74·3; H, 4·4%).

Methyl 3-O-p-*Hydroxybenzoylgallate*.—A solution of methyl 3-*p*-benzyloxybenzoyl-4,5-diphenylmethylenedioxybenzoate (4·99 g.) in tetrahydrofuran (50 c.c.) was reduced in the presence of 10% palladium–charcoal (0·5 g.) until hydrogen uptake (624 c.c.) was complete, then evaporated under reduced pressure and the product was extracted with benzene to remove diphenylmethane. *Methyl* 3-O-p-*hydroxybenzoylgallate* (1·80 g.) crystallised from ethyl acetate–benzene in prisms, m. p. 210° (Found: C, 59·3; H, 4·4. $C_{15}H_{12}O_7$ requires C, 59·2; H, 4·0%), $\nu_{max.}$ (KBr disc) 1728 and 1709 cm.$^{-1}$.

Methyl 4,5-*Diphenylmethylenedioxy*-3-(*tri*-O-*benzylgalloyloxy*)*benzoate*.—Tri-*O*-benzylgalloyl chloride (9·0 g.) and methyl 4,5-diphenylmethylenedioxy-3-hydroxybenzoate (6·83 g.) were dissolved in chloroform (100 c.c.) containing pyridine (8·0 c.c.). After 24 hr. the solution was washed with 2N-hydrochloric acid and water, and dried (Na_2SO_4), and the solvent was removed under reduced pressure. The residual oil was taken up in benzene–ethyl acetate (3 : 1; 50 c.c.) and filtered through a column of alumina (100 g.), and washing continued with the same solvent.

XUM

Removal of the solvent from the eluate gave an oily *ester* which crystallised from ethyl acetate–ethanol in slender needles (8·0 g.), m. p. 102—104° (Found: C, 76·8; H, 5·3. $C_{49}H_{38}O_9$ requires C, 76·4; H, 4·9%).

Methyl m-*Digallate* (I; R = 3,4,5-trihydroxyphenyl).—Methyl 4,5-diphenylmethylenedioxy-3-(tri-*O*-benzylgalloyloxy)benzoate (2·5 g.) was reduced in ethyl acetate (25 c.c.) in presence of 10% palladium–charcoal (0·289 g.). *Methyl* m-*digallate*, crystallised from acetone–benzene and then from ethyl acetate–light petroleum (b. p. 40—60°), was obtained as small prisms (1·07 g.), m. p. 230—232° (Found: C, 53·4; H, 3·6. Calc. for $C_{15}H_{12}O_9$: C, 53·6; H, 3·6%). (Fischer, Bergmann, and Lipschitz [6] give m. p. 175° for a monohydrate.) Methyl *m*-digallate (in a KBr disc) showed infrared peaks at 1710 and 1699 cm.$^{-1}$.

Methyl 3-O-*Benzoylprotocatechuate* (III).—After 12 hr. a mixture of benzoyl chloride (7·5 g.) and methyl protocatechuate (8·4 g.) in ether (50 c.c.) containing pyridine (2 c.c.) was diluted with ethyl acetate (50 c.c.), washed with 2N-hydrochloric acid (75 c.c.) and water, and dried (Na_2SO_4). After removal of the solvents the resultant gum was extracted with boiling water, and the residue separated from benzene–light petroleum (b. p. 60—80°) in prisms (10·0 g.), m. p. 152—153° (Found: C, 65·9; H, 4·3. Calc. for $C_{15}H_{12}O_5$: C, 66·1; H, 4·4%). Fischer, Bergmann, and Lipschitz [6] give m. p. 153—155°.

Methyl Tri-O-*benzylgalloyloxybenzoate*.—Tri-*O*-benzylgalloyl chloride (4·6 g.) in chloroform (50 c.c.) was added to a solution of methyl *p*-hydroxybenzoate (1·5 g.) in chloroform (50 c.c.) containing pyridine (8·0 c.c.). After 12 hr. and dilution with ethyl acetate (200 c.c.) the solution was washed with dilute hydrochloric acid (3 × 100 c.c.) and water, and dried (Na_2SO_4). The solution was filtered through a small column of alumina and evaporation of the filtrate gave the *diester* which crystallised from ethyl acetate–light petroleum (b. p. 60—80°) in colourless needles (4·8 g.), m. p. 127—128° (Found: C, 75·3; H, 5·4. $C_{36}H_{30}O_7$ requires C, 75·3; H, 5·3%).

Methyl p-*Galloyloxybenzoate* (IV).—Methyl *p*-tri-*O*-benzylgalloyloxybenzoate (1·8 g.) was reduced in ethyl acetate (50 c.c.) in presence of 10% palladium–charcoal (0·5 g.); the *product* separated from ethyl acetate in colourless needles (0·7 g.), m. p. 207—208° (Found: C, 58·9; H, 4·2. $C_{15}H_{12}O_7$ requires C, 59·2; H, 3·9%), $\nu_{max.}$ (in KBr) 1713 and 1682 cm.$^{-1}$.

Methyl Tris(*tri*-O-*benzylgalloyl*)*gallate*.—Methyl gallate (0·46 g.) and tri-*O*-benzylgalloyl chloride (4·6 g.) were dissolved in chloroform (30 c.c.) containing pyridine (3·0 c.c.) and kept for 4 days, then further chloroform (30 c.c.) was added and the solution washed with 2N-hydrochloric acid and water, and dried ($MgSO_4$). Removal of the solvent gave an oil which was dissolved in benzene (50 c.c.) and chloroform (50 c.c.) and filtered through alumina (65 g.). Evaporation of the solvents from the eluate gave an oily *product* which crystallised from ether–light petroleum (b. p. 40—60°) in fine needles (2·8 g.), m. p. 107° (Found: C, 76·3; H, 5·4. $C_{92}H_{74}O_{17}$ requires C, 76·2; H, 5·1%), $\nu_{max.}$ (in KBr) 1740 cm.$^{-1}$.

Methyl Tri-O-*galloylgallate* (VI; R = 3,4,5-trihydroxybenzoyl).—Methyl tris(tri-*O*-benzylgalloyl)gallate (0·5 g.) was reduced in the presence of 10% palladium–charcoal (0·06 g.) in ethyl acetate (12 c.c.). The *product* crystallised from ethyl acetate–light petroleum (b. p. 60—80°) in small plates (0·17 g.), m. p. 208—212° (decomp.) (Found: C, 54·2; H, 3·4. $C_{29}H_{20}O_{17}$ requires C, 54·5; H, 3·0%), $\nu_{max.}$ (in KBr) 1726 cm.$^{-1}$. Hydrolysis with 10% hydrochloric acid for 5 hr. gave gallic acid.

Methyl 4-O-*Benzyl*-3,5-*di*-O-(*tri*-O-*benzylgalloyl*)*gallate*.—Methyl 4-*O*-benzylgallate (0·82 g.) and tri-*O*-benzylgalloyl chloride (4·13 g.) were dissolved in chloroform (50 c.c.) and pyridine (2·4 c.c.) and kept for 3 days. After dilution with chloroform (50 c.c.) the solution was washed with 2N-hydrochloric acid and water, dried ($MgSO_4$), and evaporated to 25 c.c. Benzene (25 c.c.) was added and the solution filtered through neutralised alumina (30 g.). Removal of the solvents gave an *ester* which crystallised in fine needles (from ethyl acetate), m. p. 152° (Found: C, 75·8; H, 5·5. $C_{71}H_{58}O_{13}$ requires C, 76·2; H, 5·2%).

Methyl 3,5-*Di*-O-*galloylgallate* (VI; R = H).—Methyl 4-*O*-benzyl-3,5-di-*O*-(tri-*O*-benzylgalloyl)gallate (10·7 g.) was hydrogenated in ethyl acetate (50 c.c.) with 10% palladium–charcoal (0·1 g.) as catalyst. When the uptake of hydrogen had ceased, the catalyst was removed and the solvent evaporated; the residual *hydroxy-ester* separated from ethyl acetate–benzene in crystals, m. p. 195—200° (decomp.) (Found: C, 53·8; H, 3·3. $C_{22}H_{16}O_{13}$ requires C, 54·1; H, 3·3%).

Methanolysis of Substrates.—A 0·5% solution (0·5 c.c.) of the substrate in a mixture of 0·1N-sodium acetate buffer pH 5 (7 parts) and methanol (3 parts) was incubated at 37° for 12 hr.

XUM

and then chromatographed in two dimensions on Whatman No. 1 chromatography paper with the solvent systems 6% aqueous acetic acid and butan-2-ol–acetic acid–water (14 : 1 : 5). The position of the *o*-dihydric phenols was located with a ferric chloride–potassium ferricyanide [15] spray, and the products were identified with standard marker substances. Neutral esters were identified as described below in the case of methyl benzoate.

Methanolysis of Methyl 3-O-*Benzoylprotocatechuate* (III).—Methyl 3-*O*-benzoylprotocatechuate (0·9 g.) was dissolved in methanol (10 c.c.) containing 0·5N-sodium acetate buffer (1·0 c.c.; pH 6·0) and incubated at 37° for 24 hr. The solvents were removed on a rotary evaporator at 30°, the residue was dissolved in ether (40 c.c.), and phenolic material was removed in 2N-sodium hydroxide (20 c.c.). Evaporation of the ethereal solution at 40° gave an oil with a strong ester odour which was distilled (bath-temp. 205°), to give a colourless oil (0·06 g.). 10% Ethanolic sodium hydroxide (5 c.c.) was added to the oil, and the solution was refluxed for 1 hr., cooled, and acidified with concentrated hydrochloric acid. The crystals which separated had m. p. 120°, alone and on admixture with benzoic acid. Benzoic acid was also identified by paper chromatography on Whatman No. 1 chromatography paper in the system butan-1-ol saturated with aqueous ammonia; [16] the acids were revealed with a spray of B.D.H. universal indicator adjusted to pH 9·0.

Bistri-O-benzylgalloyloxyethane.—Ethyleneglycol (1·01 g.) and tri-*O*-benzylgalloyl chloride (18·0 g.) were dissolved in chloroform (65 c.c.) containing quinoline (8·2 g.), and the solution heated at 60° for 10 days with the exclusion of moisture. The mixture was diluted with chloroform (200 c.c.) and washed successively with 2N-hydrochloric acid (2 × 75 c.c.), water, sodium hydrogen carbonate solution, and finally water. After drying of the chloroform solution ($CaCl_2$) the solvent was removed and the residue crystallised several times from aqueous acetone. *Bistri-O-benzylgalloyloxyethane* (11 g.) crystallised in small needles, m. p. 141° (Found: C, 76·7; H, 5·6. $C_{58}H_{50}O_{10}$ requires C, 76·8; H, 5·5%).

Digalloyloxyethane.—A solution of bistri-*O*-benzylgalloyloxyethane (2·0 g.) in tetrahydrofuran (100 c.c.) was reduced in presence of 10% palladium–charcoal (0·133 g.) until uptake of hydrogen (260 c.c.) was complete. The product crystallised from water–acetone (2 : 3) in slender needles which did not melt below 260° (Found: C, 52·1; H, 4·4. Calc. for $C_{16}H_{14}O_{10}$: C, 52·4; H, 3·9%). Fischer and Bergmann [17] give no m. p. below 289°.

Tri-O-galloylglycerol.—Tri-*O*-galloylglycerol was prepared by Schmidt and Blank's method.[18]

Cyclohexane-cis-1,2-*diol Bistri-O-benzylgallate.*—Cyclohexane-*cis*-1,2-diol [19] (0·7 g.) and tri-*O*-benzylgalloyl chloride (11·0 g.) in chloroform (60 c.c.) containing quinoline (5 g.) were heated at 60° for 20 days. The product, isolated as described above for bistri-*O*-benzylgalloyloxyethane, was dissolved in benzene (75 c.c.) and filtered through a column of activated alumina (200 g.). The column was washed with benzene (150 c.c.) and removal of the benzene from the eluate gave an oily *ester* which separated from acetone in needles (3·4 g.), m. p. 129° (Found: C, 77·6; H, 6·1. $C_{82}H_{58}O_{10}$ requires C, 77·5; H, 5·9%).

Cyclohexane-cis-1,2-*diol Digallate.*—The above gallate (1·3 g.) was hydrogenated in tetrahydrofuran (150 c.c.) with 10% palladium–charcoal (0·11 g.). Removal of the solvent and crystallisation of the product from aqueous acetone gave *cyclohexane*-cis-1,2-*diol digallate* in small rhombs (0·5 g.), m. p. 222° (Found: C, 56·8; H, 4·8. $C_{20}H_{20}O_{10}$ requires C, 57·1; H, 4·8%).

Cyclohexane-trans-1,2-*diol Bistri*-O-*benzylgallate.*—Cyclohexane-*trans*-1,2-diol [20] (1·2 g.) and tri-*O*-benzylgalloyl chloride (10·0 g.) in chloroform (50 c.c.) containing quinoline (5 g.) were heated for 10 days at 60°. The *product*, isolated as described above for the *cis*-isomer, crystallised from acetone in slender needles (8·2 g.), m. p. 111° (Found: C, 77·3; H, 6·0%).

Cyclohexane-trans-1,2-*diol Digallate.*—The above *trans*-ester (1·5 g.), reduced as described above for the *cis*-isomer, gave a *product* that crystallised from aqueous acetone in irregular prisms (0·48 g.), m. p. 150° (Found: C, 56·7; H, 4·9%).

Hydrolysis of Gallates.—(a) *By alkali.* The gallate (0·09 g.) was added to 25% potassium hydroxide solution (1 c.c.), through which a brisk stream of oxygen-free nitrogen was passed.

[15] Kirby, Knowles, and White, *J. Soc. Leather Trades' Chemists*, 1953, **37**, 283.
[16] Fewster and Hall, *Nature*, 1951, **168**, 78.
[17] Fischer and Bergmann, *Ber.*, 1918, **51**, 1760.
[18] Schmidt and Blank, *Ber.*, 1956, **89**, 287.
[19] Clark and Owen, *J.*, 1949, 365.
[20] Adkins and Roebuck, *J. Amer. Chem. Soc.*, 1950, **72**, 3639.

The temperature was kept at 0°, and after 1, 3, 6, 12, and 24 hr. samples (0·2 c.c.) were withdrawn, neutralised with glacial acetic acid (0·12 c.c.), and passed down a column (3 × 1 cm.) of Dowex " 50 " to remove potassium ions, and the hydrolysate was collected in water (5 c.c.). After concentration to 0·5 c.c. at 30° in a rotary evaporator the sample was analysed by paper chromatography as outlined on p. 1841.

(b) *By acid.* The gallate (0·004 g.) was heated at 100° for 2 hr. with 10% hydrochloric acid (0·1 c.c.) and sampled after 0·5, 1, 1·5, and 2 hr. The sample was spotted directly on to Whatman No. 1 chromatography paper and chromatographed as described on p. 1841.

The gallates and their hydrolysis products had the following R_F values in (*a*) 6% aqueous acetic acid and (*b*) s-butyl alcohol–acetic acid–water (14 : 1 : 5) respectively. Di-*O*-galloyloxyethane (0·06, 0·45); ethylene glycol monogallate (0·52, 0·59); tri-*O*-galloylglycerol (0·06, 0·54); 1,2-di-*O*-galloylglycerol (0·13, 0·41); 1,3-di-*O*-galloylglycerol (0·23, 0·47); 1-*O*-galloylglycerol (0·64, 0·51); 2-*O*-galloylglycerol (0·56, 0·46); cyclohexane-*cis*-1,2-diol digallate (0·29, 0·79); cyclohexane-*cis*-1,2-diol monogallate (0·63, 0·74); cyclohexane-*trans*-1,2-diol digallate (0·36, 0·82); cyclohexane-*trans*-1,2-diol monogallate (0·59, 0·85); methyl tri-*O*-galloylgallate (VI; R = 3,4,5-trihydroxybenzoyl) (0·36, 0·70); gallic acid (0·52, 0·63); *m*-digallic acid (X) (0·25, 0·73).

The designation of the products of hydrolysis of tri-*O*-galloylglycerol was deduced from the rates of hydrolysis of the various compounds and from the knowledge that esters of primary alcohols undergo more rapid hydrolysis than those of secondary alcohols.

We thank the University of Sheffield for a Henry Ellison Fellowship to H. J. R., and the Department of Scientific and Industrial Research for a studentship to S. D. M.

CHEMISTRY DEPARTMENT,
THE UNIVERSITY, SHEFFIELD, 10. [*Received, November 9th,* 1960.]

---

360. *Gallotannins. Part III.* The Constitution of Chinese, Turkish, Sumach, and Tara Tannins.*

By R. ARMITAGE, G. S. BAYLISS, J. W. GRAMSHAW, E. HASLAM, R. D. HAWORTH, K. JONES, H. J. ROGERS, and T. SEARLE.

The isolation and purification of the tannins of Chinese galls and the leaves of Sicilian and Stagshorn sumach are described, and analysis suggests the products are essentially the same octa- or nona-galloylated glucose. The presence of a glucose core is established by hydrolysis with the purified esterase obtained from tannase (Part I). By using the methanolysis reaction (Part II) it is shown that the gallotannin contains a β-penta-*O*-galloylglucose nucleus to which some three or four additional galloyl groups are attached by depsidic linkages, and evidence is advanced favouring the presence of chains containing at least three galloyl residues. β-Penta-*O*-galloylglucose has been synthesised from tri-*O*-benzylgalloyl chloride and β-glucose, with subsequent hydrogenolysis, and the amorphous product is indistinguishable from the major methanolysis product of gallotannin. β-Tetra-*O*-galloylglucose has also been prepared synthetically and is indistinguishable from a minor methanolysis product of Chinese gallotannin or the tannin of old sumach leaves.

Preliminary results of an investigation of Turkish gallotannin are described, and the main constituent of tara tannin is shown to be based upon a new galloylated quinic acid type of structure, probably containing four or five galloyl groups united to a quinic acid nucleus.

FISCHER,[1] Freudenberg,[2] and Karrer *et al.*[3] in their classical researches on the gallotannins concluded that these were not only mixtures of isomers but also of substances

* Part II, preceding paper.

[1] Fischer, *Ber.*, 1919, **52**, 809.
[2] Freudenberg, " Naturliche Gerbstoffe," Verlag Chemie, Berlin, 1920, p. 101.
[3] Karrer, Salomon, and Payer, *Helv. Chim. Acta*, 1923, **6**, 17.

XUM

of differing empircal formulæ all having in common a galloylated glucose structure. More recently White [4] has claimed that alkaline hydrolysis of Chinese gallotannin gave rise to a substance identified on the basis of paper chromatography as a tri- or tetra-saccharide and he suggested that this was the carbohydrate core of the tannin. Grassmann, Stiefenhofer, and Endres [5] hydrolysed the methylated tannins from Sicilian and Stagshorn sumach and after removal of the 3,4,5-tri-*O*-methyl- and 3,4-di-*O*-methyl-gallic acid the carbohydrate core was isolated and separated from inorganic salts by paper electrophoresis. The carbohydrate then behaved on a paper chromatogram as a tetrasaccharide, and on acid-hydrolysis gave the component monosaccharides which were again identified by paper chromatography. Grassmann *et al.* were thus able to formulate the carbohydrate core of the gallotannin from Sicilian sumach (and Stagshorn sumach for which similar results were obtained) as a tetrasaccharide composed of one arabinose, one rhamnose, and two glucose units.

In the present investigations of the gallotannins one of the first aims, in view of these conflicting ideas, was to determine the nature of the carbohydrate core and then to establish the nature and the extent of esterification by gallic acid, but an examination of the methods of isolation and analysis of the gallotannins and the consequent application of more modern techniques was an essential preliminary to these problems. Recent work [6] has clearly shown that the tannin extracts are much more complex in composition than was previously realised; for example, paper chromatography has shown the myrobalans extract to consist of at least forty substances. Two-dimensional paper chromatograms of the crude tannin from aqueous or aqueous-acetone extracts of Chinese galls (*Rhus semialata*), Turkish or Aleppo galls (*Quercus infectoria*), the leaves of Stagshorn and Sicilian sumach (*Rhus typhina* and *Rhus coriaria*) and the pods of tara (*Caesalpinia spinosa*) similarly revealed complex mixtures of polyphenolic materials. The tannin was separated from these extracts in a chromatographically pure state by a number of methods varying with the source and nature of the extract. The gallotannins from Chinese galls and Aleppo galls were obtained free from acids and minor polyphenols by ethyl acetate extraction of an aqueous solution of the crude extract adjusted to pH 6·8. Similar treatment of crude Sicilian and Stagshorn sumach extract gave the gallotannin contaminated with materials of a flavanoid nature which, however, were removed by chromatography on Perlon powder. Tara tannin had acidic properties and was separated from other components of the extract by distribution between ethyl methyl ketone and water. In all cases the gallotannins were obtained as light amorphous solids by evaporation of solutions in acetone or by freeze-drying from t-butyl alcohol. The extremely hygroscopic nature of the gallotannins necessitated care in drying and presented many difficulties in weighing and microanalysis.

The constitution of the carbohydrate core of these tannins was investigated by the use of the carbohydrase-free galloyl esterase whose separation from the enzyme tannase has been described previously in Part I of this series.[7] Since this enzyme has no activity against oligosaccharide linkages the sugar resulting from its action on the gallotannins must represent the latter's complete carbohydrate core. Thus Chinese, Sicilian, and Stagshorn sumach gallotannins, when hydrolysed by this esterase, liberated glucose as the only carbohydrate. Similar conclusions resulted from a study of the alkaline hydrolysis of the methylated tannins (prepared by the action of diazomethane in acetone) under conditions which would not be expected to break any polysaccharide linkages. After removal of the methylated gallic acids by continuous ether-extraction and cations by an Amberlite resin, glucose was the only carbohydrate detected by paper chromatography.

[4] White, "The Chemistry of Vegetable Tannins," Soc. Leather Trades' Chemists, Croydon, 1956, p. 13.
[5] Grassmann, Stiefenhofer, and Endres, *Ber.*, 1956, **89**, 454.
[6] Kirby, Knowles, and White, *J. Soc. Leather Trades' Chemists*, 1951, **35**, 338; 1952, **36**, 148.
[7] Haslam, Haworth, Jones, and Rogers, *J.*, 1961, 1829.

XUM

For the Chinese and Sumach gallotannins the glucose was isolated after hydrolysis of the methylated material and characterised by its optical rotation and its β-penta-acetate. These results, whilst agreeing with those of Fischer,[1] Freudenberg,[2] and Karrer *et al.*,[3] are at variance with the more recent work of White [4] on Chinese gallotannin and of Grassmann and his colleagues [5] on the sumach gallotannins. During the course of our work White's conclusions have been withdrawn [6] and there is little doubt that the failure to remove inorganic salts from the alkaline hydrolysate of the tannins interfered with the paper-chromatographic analysis. We have confirmed Partridge's observations [9] that the presence of inorganic salts during paper chromatography may modify the R_F value of glucose until it simulates the behaviour of a tri- or tetra-saccharide. More difficulty was experienced in accounting for the results of Grassmann *et al.*[5] Some of the discrepancies may arise from contamination of the tannin with flavanoid material, and both rhamnose and glucose have been detected in the hydrolysis products of the flavanoids present in the sumach extract. Recently, however, at the Symposium of the Plant Phenolics Group at Egham, April 21st to 22nd, 1960, Dr. Endres kindly informed us that these results had been obtained from a tannin believed to be that of Stagshorn sumach, but that all attempts to reproduce the results with authentic samples of Stagshorn and Sicilian sumach have been unsuccessful; the tannins yielded only glucose and gallic acid on hydrolysis, thus confirming our views on the nature of the carbohydrate core of the sumach gallotannins.

TABLE 1.

Tannin	C (%)	H (%)	Gallic acid (%) *a*	Gallic acid (%) *b*	Glucose (%)	$[\alpha]_D^{20}$ (*c* 2 in acetone)
Chinese	53·2	4·0				
	53·1	4·0	102	99·4	12·1	+12·1°
	53·2	4·1	102	98·8	12·1	
Sicilian sumach	53·4	3·5		98·2	12·4	+12·6
	53·6	4·0			12·2	+12·2
Stagshorn sumach ...	53·3	4·0		97·8	12·1	
					11·7	+12·1
Turkish	53·8	4·1		97·5	16·4	+23·2
	53·2	4·0			16·5	+21·7

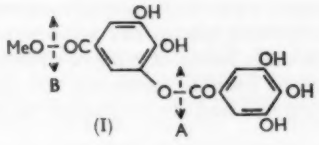
Analyses for carbon, hydrogen, gallic acid, and glucose and the $[\alpha]_D$ values of the gallotannins from Chinese galls and from Stagshorn and Sicilian sumach are shown in Table 1 and are in such close agreement as to indicate the identity of these substances with one another. The gallic acid content of the gallotannins was determined, after hydrolysis with tannase, by measurement of the optical density at 280 mμ (*a*, Table 1) or by titration of the gallic acid liberated an enzymic hydrolysis (*b*, Table 1), and the glucose was estimated after removal of the gallic acid on a column of Amberlite C.G. 400 by the method of Park and Johnson [10] in which anthrone is used. The amounts of glucose and gallic acid, which relate to the amounts of each substance liberated on hydrolysis, suggested structures containing 8—9 galloyl groups per glucose molecule, in reasonable agreement with Fischer's average formulation of Chinese gallotannin as a penta-*m*-digalloylglucose. However, the glucose and optical-rotation figures for Turkish gallotannin differ from those of the other gallotannins, and paper chromatography indicated that purification had been less successful in this case although it is not possible to decide whether the divergent figures are due to the presence of impurities or to significant structural difference. During the remainder of this paper, therefore, the term gallotannin will refer to the tannin from Chinese galls and Sicilian and Stagshorn sumach.

The arrangements of galloyl groups in the tannins was first derived from analysis of the ratio of the 3,4-di-*O*-methyl- and 3,4,5-tri-*O*-methyl-gallic acid liberated by hydrolysis

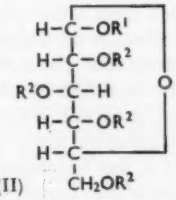
[6] White and King, *Chem. and Ind.*, 1958, 683.
[9] Partridge, *Nature*, 1949, **164**, 443.
[10] Park and Johnson, *J. Biol. Chem.*, 1949, **181**, 150.

of the methylated tannin. The total amount of acid liberated on hydrolysis was determined by titration and the proportion of 3,4-di-*O*-methylgallic acid found by measurement of the colour developed with Folin's reagent.[11] The ratio of the two methylated acids from Chinese gallotannin methylated with diazomethane was approximately 1 : 1 and indicated the presence of as many gallic acid residues linked as depsides as there were linked as normal aliphatic esters in the original tannin; this agrees approximately with figures derived by Fischer, based on the weights of the two acids isolated on hydrolysis of methylated gallotannin.

Further evidence of the extent of the depside linkages between the gallic acid residues in the tannins was derived by partial degradation of the tannin with aqueous methanol at pH 5—6; under these conditions methanolysis of the depside linkages, *e.g.*, A in formula (I), occurred to yield methyl gallate, but aliphatic ester linkages, *e.g.*, B in formula (I), were unaffected as described in Part II.[12] In order to prevent secondary reactions, probably due to oxidation, it was preferable to carry out methanolysis of the gallotannins in an atmosphere of nitrogen. After 7 days' methanolysis of Chinese and sumach gallotannins, paper chromatography revealed the presence of methyl gallate, a trace of gallic acid, and two galloylated glucoses (C) and (D) of which (C) constituted some two-thirds of the total methanolysis products. Paper-chromatographic analysis at an intermediate stage showed the presence of methyl *m*-digallate (I), thus indicating chains of at least



(I)



(II)

three galloyl groups in the tannin. The two galloylated glucoses were separated by chromatography on cellulose powder and the major component (C) was obtained as an amorphous powder, homogeneous on the basis of paper chromatography and counter-current distribution experiments, which gave analytical figures agreeing closely with those required by a penta-*O*-galloylglucose. The identification was supported by methylation, first with diazomethane and then with methyl iodide and silver oxide, to a product which on hydrolysis gave glucose and 3,4,5-tri-*O*-methylgallic acid uncontaminated with di-*O*-methylgallic acid. β-Penta-*O*-galloylglucose (II; $R^1 = R^2 = 3,4,5$-trihydroxybenzoyl) was therefore synthesised; as Fischer and Bergmann's method[13] using tri-*O*-acetylgalloyl chloride has been shown[14] to give a mixture, tri-*O*-benzylgalloyl chloride was treated with β-glucose and pyridine in chloroform, to yield amorphous β-pentakis-*O*-(tri-*O*-benzylgalloyl)glucose which on hydrogenation afforded β-penta-*O*-galloylglucose. The amorphous powder gave analytical figures and optical-rotation and optical-density values identical with those of the major methanolysis product (C) of the gallotannin, which was indistinguishable from the latter by paper-chromatographic and counter-current analysis. Both the methanolysis product and the synthetic specimen were recovered unchanged when subjected to further methanolysis in absence of air, and at 100° both showed a change in optical rotation and of paper-chromatographic pattern probably as a result of partial isomerisation. When freeze-dried from glacial acetic acid and analysed by paper chromatography, both samples were partly transformed into a compound of unknown constitution, but the product reverted completely to β-penta-*O*-galloylglucose when subjected

[11] Swain and Hillis, *J. Sci. Food Agric.*, 1959, **11**, 63.
[12] Preceding paper.
[13] Fischer and Bergmann, *Ber.*, 1918, **51**, 1760.
[14] Asquith, *Nature*, 1951, **168**, 3738.

XUM

to methanolysis. The effects of heat and glacial acetic acid on β-penta-*O*-galloylglucose are being studied more closely.

The minor component (D) of the galloylated glucose mixture derived from the methanolysis of the tannins was less readily available, but analysis suggested a tetra-*O*-galloylglucose structure, and methylation followed by hydrolysis gave 3,4,5-tri-*O*-methylgallic acid free from di-*O*-methylgallic acids. Controlled hydrolysis of β-pentakis-*O*-(tri-*O*-benzylgalloyl)glucose gave a crystalline substance, formulated as β-2,3,4,6-tetrakis-*O*-(tri-*O*-benzylgalloyl)glucose. Hydrogenation of this crystalline substance gave an amorphous compound identical analytically and paper-chromatographically with the minor component (D) which is provisionally regarded as β-2,3,4,6-tetra-*O*-galloylglucose (II; $R^1 = H$, $R^2 = 3,4,5$-trihydroxybenzoyl) since it gave a positive reaction with aniline hydrogen phthalate [15] indicative of a potential aldehyde group.

The presence of the small amount of β-tetra-*O*-galloylglucose in the anærobic methanolysis products of the gallotannins requires further consideration. Thus Chinese and sumach gallotannins may be mixtures of closely related substances, the majority of which have as their basic core β-penta-*O*-galloylglucose, together with a small proportion which have a β-tetra-*O*-galloylglucose core. Alternatively, the small amounts of β-tetra-*O*-galloylglucose may arise initially by a partial breakdown of the natural tannin before or during isolation. To test this supposition freshly collected leaves of Stagshorn sumach were extracted at 20° with ethyl acetate to give an extract free from gallic acid, and the tannin was purified from chlorophyll and other impurities by chromatography on Perlon powder at 0°. Methanolysis of this tannin gave β-penta-*O*-galloylglucose and methyl gallate only, thus indicating that the naturally occurring tannin has a β-penta-*O*-galloylglucose core which may be modified by changes in older leaves or galls or during isolation of the tannin. However, it is not inferred that the tannins themselves are homogeneous and further work is in progress using counter-current and electrophoretic methods to test the nature and extent of any heterogeneity.

The occurrence of methanolysis may also explain some anomalous results of earlier workers; thus Fischer and Freudenberg [16] and Herzig [17] isolated methyl 3,4,5-tri-*O*-methylgallate and penta-*O*-methyl-*m*-digallate respectively on methylation of tannins with diazomethane in methanol. The alcoholysis is, in addition, of practical consequence in the extraction of tannins. Some workers, including Iljin,[18] have recommended the use of ethanol for tannin extractions, but the products differ considerably from those used by Fischer which were obtained by aqueous extraction. Thus prolonged extraction or evaporation with aqueous ethanol leads to the production of ethyl gallate which has been isolated by chloroform-extraction and identified. The residual tannin contained 13·6% of glucose and must therefore be partially degraded; criticism of Fischer's work based on the analysis of such materials is obviously invalid. Also there is no evidence to support White's [4] claim that penta-*O*-galloylglucose occurs in gallotannin extracts since the paper-chromatographic spot used for the identification of the penta-*O*-galloylglucose can be ascribed to ethyl gallate produced by ethanolysis of the tannin.

Tara tannin was different from the gallotannins described above in its pronounced acidic character,[19] and hydrolysis with the galloyl esterase from tannase gave gallic and quinic acid, thus revealing a hitherto unknown type of galloylated quinic acid tannin structure. These conclusions were confirmed by isolation of both gallic and quinic acid after acid-hydrolysis of the tannin. Analysis of the gallic and quinic acid in the tannin indicated a ratio of 4—5 : 1. The gallic acid was determined as outlined for Chinese and sumach gallotannins, and the quinic acid by titration of the free carboxyl group of the

[15] Hough, *J.*, 1950, 1702.
[16] Fischer and Freudenberg, *Ber.*, 1914, **47**, 2485.
[17] Herzig, *Ber.*, 1923, **56**, 221.
[18] Iljin, *Ber.*, 1914, **47**, 485.
[19] Burton and Nursten, " The Chemistry of Vegetable Tannins," Soc. Leather Trades' Chemists, Croydon, 1956, p. 61.

XUM

tannin, but alternative methods for the analysis of quinic acid are being developed and it is hoped more accurate analyses will soon be available. Methanolysis of tara tannin yielded methyl gallate and a complex mixture of galloylated quinic acid derivatives which have not yet been separated.

Investigations of the possibilities of separating the natural tannins by counter-current and electrophoretic methods, and further studies on Turkish and tara tannin, are in progress.

Experimental

"Light petroleum" refers to the fraction of b. p. 60—80° and alumina to Peter Spence's grade "H." Unless otherwise stated, quantitative determinations on gallotannins and galloylated glucoses were made on samples dried to constant weight at 105°/0·005 mm.

Solutions were concentrated at 25—30° under reduced pressure with a rotary evaporator.

Paper Chromatography.—Whatman No. 2 paper was used except where otherwise stated, and chromatograms were developed at 20° ± 3°.

(i) *Phenols.* Substances were chromatographed in two dimensions with solvent systems composed of (*a*) 6% acetic acid and (*b*) butan-2-ol–acetic acid–water (14 : 1 : 5). *o*-Dihydroxyphenols were revealed with a spray (*a*) composed of ferric chloride and potassium ferricyanide,[20] and materials of a flavanoid nature were detected by their absorption or fluorescence in ultraviolet light (normally also in the presence of ammonia vapour) and also by use of a citric acid–boric acid spray (*b*),[21] which revealed these substances in ultraviolet light as green fluorescent spots.

(ii) *Carbohydrates.* Carbohydrates were chromatographed with the solvent system (*b*) above, or (*c*) composed of butan-1-ol–ethanol–water (40 : 11 : 9) and detected by sprays of silver nitrate,[22] aniline hydrogen phthalate,[15] or sodium metaperiodate and benzidine.[23]

(iii) *Methylated phenolic acids.* Substances were chromatographed two dimensionally in solvent systems (*a*) and (*b*) above or in system (*d*) composed of butan-1-ol saturated with 1·5N-ammonia and 1·5N-ammonium carbonate. Phenols with a free *para*-position and those with a carboxyl group in the *para*-position were detected by spraying with a 0·1% methanolic solution of 2,6-dibromobenzoquinone 4-chloroimide (Gibbs reagent) followed by sodium hydrogen carbonate solution.

Counter-current Distribution.—Analytical counter-current distributions were carried out with solvent systems (*e*), composed of propan-1-ol–butan-1-ol–cyclohexane–water in the ratios of 33 : 11 : 7 : 49. Tubes (upper phase 15 c.c., lower phase 10 c.c.) were homogenised by the addition of propan-1-ol (9·0 c.c.) and analysed by measurement of the optical density at 320 mμ.

Extraction of Chinese Galls and Paper Chromatography of the Extract.—Crushed Chinese galls (10 g.) were shaken with water (100 c.c.) for 2 days at room temperature, and the aqueous solution was extracted with ethyl acetate (8 × 100 c.c.). Removal of the ethyl acetate gave a gum (2 g.) which was freeze-dried from water to give a buff amorphous powder. Paper chromatography of this extract in solvent systems (*a*) and (*b*) revealed the pattern shown in Table 2.

Table 2.

Spot	R_F (*a*)	R_F (*b*)	Spray (*a*)	U.v.–NH_3	Substance
(I)	0·00—0·30	0·32—0·54	+	Absorbs	Gallotannin
(II)	0·03	0·18	+		Unknown
(III)	0·14—0·27	0·26	+	Violet	Unknown
(IV)	0·20	0·10	+		Unknown
(V)	0·30	0·74	+		Unknown
(VI)	0·33	0·72	+	Blue	*m*-Digallic acid
(VII)	0·48	0·30	+		Unknown
(VIII)	0·49	0·70	+	Blue	Gallic acid

[20] Kirby, Knowles, and White, *J. Soc. Leather Trades' Chemists*, 1953, **37**, 283.
[21] Wilson, *J. Amer. Chem. Soc.*, 1939, **61**, 2303.
[22] Trevelyan, Porter, and Harrison, *Nature*, 1950, **166**, 144.
[23] Gordon, Thornberg, and Werum, *Analyt. Chem.*, 1956, **28**, 849.

XUM

Purification of Chinese gallotannin. The aqueous extract of Chinese galls or commercial tannic acid (4·4 g.) was added to M-phosphate buffer (pH 6·8; 100 c.c.), and the solution extracted with ethyl acetate (8 × 100 c.c.) until the extract no longer reacted with ferric chloride. The ethyl acetate was removed at 30° and the residue dissolved in water (100 c.c.) and re-extracted with ethyl acetate. The resultant gum was taken up in water (10 c.c.) and freeze-dried for 12 hr. to give Chinese gallotannin (3·95 g.) as a white amorphous powder. Paper chromatography revealed in solvent systems (*a*) and (*b*) only the gallotannin, R_F (*a*) 0·00—0·30 and (*b*) 0·30—0·54.

Extraction of Sicilian or Stagshorn Sumach Leaves and Chromatography of the Extract.—Dried powdered sumach leaves (40 g.) were shaken with chloroform (100 c.c.) for 2 days, the residue was dried, and the polyphenols were removed by shaking at room temperature with 40% aqueous acetone (800 c.c.) for 24 hr. This procedure was repeated twice and the combined extracts were concentrated to 150 c.c. at 30° and extracted with ethyl acetate (8 × 100 c.c.). Removal of the ethyl acetate at 30° gave a tan-coloured gum which when freeze-dried gave a yellow powder (10 g.). Paper-chromatographic analysis in systems (*a*) and (*b*) is recorded in Table 3.

TABLE 3.

Spot	R_F (*a*)	R_F (*b*)	Spray (*a*)	Spray (*b*)	U.v.	U.v.–NH_3	Substance
(I)	0·05	0·25	—	+	—	Yellow	Unknown
(II)	0·05	0·35	—	+	—	Yellow	Unknown
(III)	0·04	0·49	—	+	—	Green	Unknown
(IV)	0·04	0·66	—	+	—	Yellow	Unknown
(V)	0·04—0·15	0·56	—	+	—	Green	Unknown
(VI)	0·13	0·68	—	+	—	Green	Unknown
(VII)	0·00—0·30	0·32—0·54	+	—	Absorbs	Absorbs	Gallotannin
(VIII)	0·10—0·23	0·44	—	+	Absorbs	Yellow	Unknown
(IX)	0·33	0·63	+	—	Absorbs	Blue	*m*-Digallic acid
(X)	0·15—0·38	0·59	+	+	Absorbs	Yellow	Unknown
(XI)	0·16—0·39	0·68	+	+	Absorbs	Yellow	Unknown
(XII)	0·21—0·38	0·75	—	+	Absorbs	Yellow	Unknown
(XIII)	0·45	0·64	+	—	—	Blue-violet	Gallic acid
(XIV)	0·50	0·60	—	—	—	Blue	Unknown
(XV)	0·53	0·27	+	—	—	Violet	Unknown
(XVI)	0·58	0·32	+	—	—	Violet	Unknown
(XVII)	0·56	0·40	+	—	—	Violet	Unknown
(XVIII)	0·54	0·56	—	—	—	Blue-green	Unknown
(XIX)	0·60	0·54	—	—	—	Blue	Unknown
(XX)	0·58	0·68	—	—	—	Blue	Unknown

Purification of Stagshorn or Sicilian sumach gallotannin. The extract (6 g.) was dissolved in methanol (20 c.c.) and chromatographed at 0° on a column of Perlon (200 g.; 60 × 3·5 cm.). At 0° methanolysis of the crude tannin did not occur and methyl gallate was not detected in the eluate. Elution at 0° with methanol (200 c.c.) removed the flavanoid material after which elution was continued with ethyl methyl ketone–water azeotrope as solvent; fractions (10 c.c.) were collected and their optical density measured at 335 mμ. After an initial peak containing the remaining flavanoids and gallic acid, the gallotannin was eluted in a peak (2 l.). Concentration of this eluate gave a gum which was freeze dried from water or t-butyl alcohol to give sumach gallotannin as a white amorphous powder (1·5 g.), R_F (*a*) 0·00—0·30 and (*b*) 0·32—0·54.

Extraction of Turkish (Aleppo) Galls and Chromatography of the Extract.—Powdered Turkish galls (10 g.) were shaken with water (100 c.c.) for 2 days at room temperature, and the aqueous solution was then extracted with ethyl acetate (8 × 100 c.c.). Removal of the ethyl acetate gave a gum (2 g.) which was freeze-dried from water to give a buff amorphous powder. Paper chromatography of this powder in solvent systems (*a*) and (*b*) revealed the pattern shown in Table 4.

Purification of Turkish gallotannin. The extract (2 g.) was purified in an identical manner to that of Chinese galls, to give Turkish gallotannin (1·4 g.) as a white amorphous powder, R_F (*a*) 0·02—0·37 and (*b*) 0·36—0·50.

Determination of Glucose in Gallotannins.—The method used was an adaption of that employed by Park and Johnson.[10] Gallotannin (10 mg.) was dissolved in 0·5N-acetate buffer

TABLE 4.

Spot	R_F (*a*)	R_F (*b*)	Spray (*a*)	U.v.–NH_3	Substance
(I)	0·02	0·27—0·41	—	Blue-green	Ellagic acid
(II)	0·02—0·37	0·36—0·50	+	Absorbs	Gallotannin
(III)	0·22	0·71	+	Blue	Unknown
(IV)	0·36	0·70	+	Blue	*m*-Digallic acid
(V)	0·39	0·33	+	Violet	Unknown
(VI)	0·47	0·65	+	Blue	Gallic acid
(VII)	0·51	0·02	+	Absorbs	Unknown
(VIII)	0·51	0·18	+	—	Unknown
(IX)	0·51	0·38	+	Absorbs	Unknown
(X)	0·55	0·30	+	Violet	Unknown
(XI)	0·60	0·32	+	Violet	Unknown
(XII)	0·68	0·45	—	Blue-violet	Unknown

pH 6·0 (2 c.c.), 0·025% tannase solution (1 c.c.) and a few drops of toluene were added, and the whole was incubated at 37° for 2 days; gallic acid was then the only phenol detectable by paper chromatography in systems (*a*) and (*b*). Samples (1 c.c.) were passed down Amberlite C.G. 400 columns (0·7 × 3 cm.), the columns were washed with distilled water, and the eluates collected in graduated flasks (10 c.c.). The volume of each was made up to 10 c.c., samples (0·2, 0·4, 0·6, 0·8, and 1·0 c.c.) were withdrawn and placed in test tubes, and distilled water was added to 1 c.c. To these solutions, cooled in ice, a mixture of ethanol and concentrated hydrochloric acid (1 : 1; 1·5 c.c.) was added followed by a 0·1% solution of anthrone in " AnalaR " 98% sulphuric acid (3 c.c.), and the solutions were mixed with a glass rod. The tubes were suspended in boiling water for 7 min., then kept at room temperature for 20 min., whereafter the optical density was measured at 620 mμ. The results were plotted and compared with the graph obtained with one or more standard glucose solutions treated similarly. Results are shown in Table 1.

Determination of Gallic Acid in Gallotannin.—(a) *Optical-density measurement.* The extinction coefficient $E^{1\,cm.}_{mole.}$ at 280 mμ of gallic acid in acetate buffer pH 6·0 was $3{\cdot}65 \times 10^3$. Gallotannin (10 mg.) was dissolved in 0·5N-acetate buffer of pH 6·0 (10 c.c.), 0·025% tannase (0·5 c.c.) added, and the solution incubated for 24 hr. at 37°. Aliquot parts (2·0 c.c.) were diluted to 100 c.c. each and the optical density measured at 280 mμ. Enzyme controls were also determined. Results are shown in Table 1.

(b) *Titration.* The theoretical end-point for the titration of gallic acid with 0·5N-sodium hydroxide was determined at 37° to be pH 6·5. Gallotannin (2 mg.) was dissolved in water (1·0 c.c.) and placed in a small cell (5 c.c.) at 37°; a fine stream of oxygen-free nitrogen passed through the solution. The pH was adjusted to 5·5 with an autotitrator, and 0·05% tannase (1 c.c.) added. As the hydrolysis proceeded addition of 0·5N-sodium hydroxide by the autotitrator maintained the pH at 5·5 and after 6 hr., when the reaction was complete, the pH was adjusted to 6·5 and the alkali consumed determined. Enzyme controls were also determined. Results are shown in Table 1.

Action of Purified Tannase Esterase on Chinese and Sumach Gallotannins.—The tannin (4 mg.) was dissolved in 0·5N-acetate buffer of pH 6·0 (4·0 c.c.) and incubated for 48 hr. with the purified tannase esterase (0·1% solution; 0·4 c.c.) prepared as described in Part I of this series. At this stage paper chromatography in solvent system (*a*) showed gallic acid to be the only phenol present. Sodium ions were removed on a small column of Dowex " 50 " (H^+), and the tannin hydrolysate was examined for sugars by paper chromatography. Similarly treated solutions of glucose, maltose, and raffinose were used as standards. Glucose, R_F (*b*) 0·20, was the only sugar detected in the tannin hydrolysates.

Isolation of Glucose from Sicilian Sumach and Chinese Gallotannin.—Sicilian sumach tannin (or Chinese gallotannin) (1·16 g.), dissolved in acetone (50 c.c.), was treated with an excess of ethereal diazomethane for 24 hr. and the process repeated twice. The solvents were removed at 30° and the residue was treated with 12% methanolic potassium hydroxide (40 c.c.) for 48 hr. at 0°, potassium ions were removed by passage down a column of ZeoKarb 215, and the resultant solution was continuously extracted with ether (4 days) to remove 3,4-di-*O*-methylgallic and 3,4,5-tri-*O*-methylgallic acid. Concentration of the aqueous phase gave a brown gum (0·133 g.) which paper-chromatographic analysis in solvent systems (*b*) and (*c*) showed to contain glucose, R_F (*b*) 0·20, as the only carbohydrate. The glucose was freeze-dried, refluxed for 3 hr. with a mixture of anhydrous sodium acetate (0·1 g.) and acetic anhydride (3 c.c.), and

XUM

poured into water (100 c.c.). The precipitated oil separated, after several crystallisations, from ethanol as crystals, m. p. 130° undepressed on admixture with glucose β-penta-acetate.

Detection of Rhamnose in Sicilian Sumach Extract.—Crude Sicilian sumach tannin (10 mg.) was hydrolysed for 24 hr. at 100° with 1% sulphuric acid (2 c.c.), and the sulphate ions were removed on a small column of Dowex " 2 " (acetate form), or alternatively by addition of 0·2M-barium hydroxide (1 c.c.) with separation of the barium sulphate on a centrifuge. The hydrolysate when examined paper-chromatographically in systems (*b*) and (*c*) was seen to contain glucose, R_F (*b*) 0·20, and rhamnose, R_F (*b*) 0·30. Examination by this procedure of the fractions obtained by chromatography on Perlon powder of this crude Sicilian sumach tannin showed rhamnose, R_F (*b*) 0·30, to be present in the flavanoids eluted with methanol.

Determination of Ratio of 3,4,5-*Tri*-O-*methylgallic and* 3,4-*Di*-O-*methylgallic Acid produced on Hydrolysis of Methylated Chinese and Sumach Gallotannin.*—The gallotannin (0·20 g.) was methylated in acetone (5 c.c.) with an excess of diazomethane as described by Fischer and Freudenberg.[24] After removal of the acetone the residue was taken up in fresh acetone (5 c.c.), methyl iodide (3 c.c.) and silver oxide (1·0 g.) were added, and the solution was refluxed for 5 days with exclusion of moisture. The silver oxide and acetone were removed, and the residual methylated gallotannin (0·20 g.) was dissolved in 12% methanolic potassium hydroxide (4·0 c.c.). After 48 hr. at 0°, the solution was diluted to 100 c.c. with water. Aliquot parts (1 c.c.) were titrated against 0·1N-hydrochloric acid to pH 7. A blank determination without the methylated gallotannin gave the total weight of the methylated acids produced on hydrolysis. The percentage of free phenol in the mixture was then determined with Folin's reagent according to the method of Swain and Hillis,[11] and the ratio of the two methylated acids liberated was then calculated.

Methanolysis of Chinese Gallotannin.—Chinese gallotannin (3 g.) was dissolved in a solution of 0·5N-acetate buffer (pH 6·0; 30 c.c.) in methanol (300 c.c.) which had previously been de-oxygenated by boiling under nitrogen; the mixture was kept at 37° for 7 days with a very slow nitrogen stream passing through it. Removal of the solvents at 30°, solution of the residue in water (100 c.c.), and extraction with ethyl acetate (7 × 100 c.c.) gave a gum which when analysed by paper chromatography in solvents (*a*) and (*b*) revealed the following pattern shown in Table 5.

TABLE 5.

Spot	R_F (*a*)	R_F (*b*)	U.v.–NH_3	Substance
(I)	0·02—0·14	0·58	Absorbs	C
(II)	0·20	0·60	Absorbs	D
(III)	0·47	0·70	Blue	Gallic acid
(IV)	0·52	0·82	Blue	Methyl gallate

The gum was dissolved in 6% aqueous acetic acid (20 c.c.) and applied to a cellulose column (B.W. 200; 6·5 × 66 cm.) packed in the same solvent. Elution was carried out with 6% acetic acid and fractions (15 c.c.) were collected and analysed by measurement of their optical density at 320 mμ. Four main peaks were thus obtained and the solvents were removed from each at 30°.

Fraction I yielded methyl gallate which recrystallised from aqueous methanol in needles (1·2 g.), m. p. and mixed m. p. 196°, R_F (*a*) 0·52, (*b*) 0·82, and fraction 2 gave gallic acid, m. p. and mixed m. p. 240°, R_F (*a*) 0·47, (*b*) 0·70. A solution of the gummy fraction 3 in acetone was filtered and evaporated at 30°. The residue was taken up in ethyl acetate (100 c.c.), washed with water (3 × 100 c.c.), and recovered at 30°. The residue, freeze-dried from water or t-butyl alcohol, yielded *component D* as a white amorphous powder (0·08 g.) (Found: C, 51·4; H, 4·0; glucose, 22·1, 22·3. $C_{34}H_{28}O_{22}$ requires C, 51·8; H, 3·6; glucose, 22·8%) with R_F (*a*) 0·20 and (*b*) 0·60. Similar treatment of fraction 4 gave *component C* as a white amorphous powder (1·08 g.) (Found: C, 52·1, 52·4; H, 3·6, 3·9; glucose, 19·0, 19·2. $C_{41}H_{32}O_{26}$ requires C, 52·3; H, 3·4; glucose, 19·2%) with R_F (*a*) 0·02—0·14, (*b*) 0·58.

Methyl Tri-O-*benzylgallate.*—This was prepared by a modification of the method described by Clinton and Geissman.[25] Methyl gallate (75 g.) was added to a stirred mixture of potassium

[24] Fischer and Freudenberg, *Ber.*, 1914, **47**, 2485.
[25] Clinton and Geissman, *J. Amer. Chem. Soc.*, 1943, **65**, 85.

carbonate (200 g.), potassium iodide (50 g.), and acetophenone (600 c.c.) at 100°. The temperature was raised to 140—150° and stirring continued in an atmosphere of carbon dioxide during the addition, in 1 hr., of benzyl chloride (220 c.c.) and then for a further 4 hr. The mixture was steam-distilled and, after cooling, the solid non-volatile product was collected. By chromatography on alumina (45 × 5·2 cm.) with benzene as eluant and crystallisation twice from ethyl acetate–light petroleum, *methyl tri-O-benzylgallate* (174 g., 94%) was obtained as colourless needles or prisms, m. p. 100·5—101·5° (Found: C, 76·7; H, 6·0. $C_{29}H_{26}O_5$ requires C, 76·6; H, 5·8%). Crystallisation from benzene–light petroleum afforded white needles of a *solvate*, m. p. 90·5—91·5° (Found: C, 77·6, 77·5; H, 6·1, 5·9. $C_{29}H_{26}O_5,\frac{1}{2}C_6H_6$ requires C, 77·9; H, 5·9%) containing benzene (Ramsden test [26]) which was eliminated by drying at 60°/0·002 mm. Clinton and Geissman [25] describe a compound, m. p. 89—90°, crystallising from benzene–light petroleum as the unsolvated form.

Tri-O-benzylgalloyl Chloride.—The foregoing ester (50 g.) was suspended in boiling methanol (400 c.c.), and 20% aqueous potassium hydroxide (46 c.c., 1·5 mol.) added during 1 hr. After a further hour on the steam-bath the solution was cooled and acidified with dilute hydrochloric acid, and tri-*O*-benzylgallic acid was collected, washed with water, dried, and crystallised from ethyl acetate–light petroleum; white needles (44 g., 91%), m. p. 191—191·5°, were obtained (Schmidt and Schach [27] give m. p. 192°). The acid was converted quantitatively into tri-*O*-benzylgalloyl chloride which separated from benzene–light petroleum in colourless needles, m. p. 116·5—117° (Schmidt and Schach [27] give m. p. 115—116°).

Pentakis-O-(tri-O-benzylgalloyl)-β-glucose.—Powdered β-glucose [28] (2·5 g.), $[\alpha]_D^3$ +18·1 ± 0·03° (*c* 9 in H_2O), tri-*O*-benzylgalloyl chloride (38·4 g., 6 mol.), pyridine (15 c.c.), and chloroform (100 c.c.) were stirred until the glucose dissolved (24—30 hr.). The pale yellow solution was heated at 61° for 18—21 days during which pyridine hydrochloride separated and the solution darkened. The cooled mixture was diluted with chloroform (250 c.c.), shaken successively with water, dilute sulphuric acid, and aqueous sodium hydrogen carbonate, dried ($MgSO_4$), and evaporated at 20°. The viscous residue was dissolved in benzene, the solution was evaporated to small volume at 20°, and *tri-O-benzylgallic anhydride* removed; crystallisation from ethyl acetate–light petroleum gave needles (3·9 g.), m. p. 166·5—167° (Found: C, 78·1; H, 5·85. $C_{56}H_{46}O_9$ requires C, 78·0; H, 5·4%). Schmidt and Schach [27] give m. p. 165·5° but no analytical results. The filtrate and benzene washings were further concentrated, freed from a second crop (1·1 g.) of anhydride, and adsorbed on ethyl acetate-washed alumina (30 × 3·5 cm.). The column was eluted with benzene (2 l.), the eluate evaporated at 20°, and the residual glass freeze-dried from benzene. After drying at room temperature and 0·002 mm., the product (30·5 g., 97·5%) was obtained as a light buff-coloured powder $[\alpha]_D^{24}$ −2·1° ± 0·3° (*c* 3 in ethyl acetate). This material was repeatedly chromatographed on ethyl acetate-washed alumina (20 × 3·5 cm.), covered by a layer (4 cm.) of alumina, with benzene (1·5 l.) as eluant until no change in optical rotation was observed. After freeze-drying, *pentakis-O-(tri-O-benzylgalloyl)-β-glucose* was obtained as a white amorphous powder (Found: C, 76·1, 76·5; H, 5·7, 5·9. $C_{148}H_{122}O_{26}$ requires C, 76·7; H, 5·4%), $[\alpha]_D^{22·5}$ −6·4° ± 0·4° (*c* 3 in ethyl acetate), readily soluble in acetone, benzene, chloroform, methylene dichloride, ether, ethyl acetate, dioxan, and tetrahydrofuran, but sparingly soluble in methanol and ethanol.

2,3,4,6-Tetrakis-O-(tri-O-benzylgalloyl)-β-glucose.—A solution of the foregoing ester (10 g.) in benzene (250 c.c.) was diluted with an equal volume of light petroleum and shaken intermittently with acetic acid-washed alumina (250 g., activated at 140—150° for 24 hr.) for 16 days at room temperature. This mixture was poured on a column (40 × 3·5 cm.), the solvents were removed, and the alumina was exhaustively eluted with benzene (2 l.) and with benzene–chloroform (1 : 1; 2 l.). Hydrogenation followed by paper chromatography indicated that the fraction (1·5 g.) recovered from benzene contained pentakis(tribenzylgalloyl)glucose, and the fraction (6·0 g.) from the benzene–chloroform eluate consisted of a mixture of tetrakis- and pentakis-(tribenzylgalloyl)glucoses. This mixture was rechromatographed on ethyl acetate-washed alumina (18 × 2 cm.), and eluted with benzene (1·5 l.), and then with benzene–chloroform (1 : 1; 1 l.). Evaporation at 25° of the benzene–chloroform eluate afforded a pale yellow glass, which was dissolved in warm ether (70 c.c.), and, after 12 hr., the gelatinous precipitate was removed and the filtrate nucleated; the first crystals were obtained by careful

[26] Bradley, Robinson, and Schwarzenbach, *J.*, 1930, 812.
[27] Schmidt and Schach, *Annalen*, 1951, **571**, 29.
[28] Hudson and Dale, *J. Amer. Chem. Soc.*, 1917, **39**, 320.

XUM

removal of the benzene followed by prolonged contact and trituration with fresh quantities of ether. After several days, 2,3,4,6-*tetrakis*-O-(*tri*-O-*benzylgalloyl*)-β-*glucose* was collected and thrice recrystallised from methylene dichloride–ether, to give colourless needles (3·15 g.) (Found: C, 76·2; H, 5·7. $C_{118}H_{100}O_{22}$ requires C, 75·8; H, 5·4%), gradually shrinking on heating to a turbid gum, which cleared at 97—98°. A further quantity (0·85 g.) was recovered from the mother-liquors.

Penta-O-*galloyl*-β-*glucose*.—The pentakis(tribenzylgalloyl)glucose (6·42 g.) in tetrahydrofuran (50 c.c.) was reduced at room temperature over 10% palladised charcoal (0·65 g.) which had been washed with water until the washings had pH 7·0. Hydrogen absorption ceased after 8 hr.; the mixture was filtered through a layer of cellulose powder, and the catalyst washed rapidly with a little deoxygenated ethanol. The filtrate and washings were evaporated at 25° and the residual glass was thrice dissolved in acetone and recovered at 25°. The product, freeze-dried from t-butyl alcohol, was a white amorphous powder (Found: C, 52·7, 52·4, 52·0; H, 3·8, 3·7, 3·7; glucose, 19·1, 18·9. $C_{41}H_{32}O_{26}$ requires C, 52·3; H, 3·4; glucose, 19·2%) with R_F (*a*) 0·02—0·14, (*b*) 0·58.

Pentagalloylglucose and compound C (above) were readily soluble in methanol, ethanol, acetone, tetrahydrofuran, ether, dioxan, and 2-methoxyethanol, moderately soluble in t-butyl alcohol, and sparingly soluble in water, but insoluble in benzene, chloroform, or light petroleum. Samples dried to constant weight at 20°/0·005 mm. gave (*c* 2 in acetone) $[\alpha]_D^{23\cdot5}$ 17·7° ± 0·3° for synthetic material, and 17·6°, 17·4° ± 0·3° for material from methanolysis of gallotannin. Counter-current distribution in solvent system (*e*) showed that both samples were homogeneous (at 20°, *K* 1·04), and the distribution pattern was unaffected on admixture. The extinction coefficient measured in solvent system (*e*) [top phase (10 c.c.), lower phase (15 c.c.), homogenised with propan-1-ol (9 c.c.)] was 6·5 × 10^3, and hydrolysis with tannase at pH 6·0 and 37° yielded glucose and gallic acid. The products were recovered after being heated with 90% aqueous methanol adjusted to pH 6·0 for 48 hr. After methylation and hydrolysis as described above, the hydrolysate was passed down a column (20 × 1·5 cm.) of ZeoKarb 215(H^+) to remove potassium ions and concentrated to 1 c.c. at 30°; paper chromatography in solvent system (*d*) and spraying with Gibbs's reagent showed only 3,4,5-tri-*O*-methylgallic acid.

2,3,4,6-*Tetra*-O-*galloyl*-β-*glucose*.—2,3,4,6-Tetrakis-*O*-(tri-*O*-benzylgalloyl)-β-glucose (0·504 g.) was reduced as described for the preparation of pentagalloylglucose (above). The product, after freeze-drying from t-butyl alcohol, was a colourless amorphous powder (Found: C, 52·1; H, 4·0; glucose, 22·4, 22·5. $C_{34}H_{28}O_{22}$ requires C, 51·8; H, 3·6; glucose, 22·8%) with R_F (*a*) 0·20, (*b*) 0·60; $[\alpha]_D^{24\cdot5}$ 55·4° ± 0·6° (*c* 2 in acetone).

2,3,4,6-*Tetragalloylglucose* and compound D (above) had solubilities as described for pentagalloylglucose and gave brown colours with aniline hydrogen phthalate in moist butan-1-ol (under similar conditions pentagalloylglucose gave no colour). Methylation and hydrolysis gave 3,4,5-tri-*O*-methylgallic acid only.

Isolation of Ethyl Gallate from Chinese Galls Extracted with Ethanol.—Crushed Chinese galls (5 g.) were extracted by shaking with 50% aqueous ethanol (250 c.c.) for 48 hr. The extract was concentrated at 30° to 100 c.c., adjusted to pH 6·8 with 0·2M-potassium dihydrogen phosphate (50 c.c.) and M-potassium hydroxide and extracted with ethyl acetate (4 × 150 c.c.). Removal of the ethyl acetate and freeze-drying of the residue gave a buff-coloured powder (1·2 g.) which paper-chromatographic analysis showed to contain the gallotannin and a substance with R_F (*a*) 0·55 and (*b*) 0·88, giving a positive reaction with the spray (*a*). The tannin extract was continuously extracted with chloroform (Soxhlet) for 96 hr.; removal of the chloroform gave a yellow gum from which ethyl gallate was obtained by sublimation (100°/0·05 mm.) and recrystallisation from methanol–water as needles (0·08 g.), m. p. and mixed m. p. 140°. Ethyl gallate subjected to paper-chromatographic analysis had R_F (*a*) 0·55 and (*b*) 0·88.

Extraction of Pods of Caesalpinia spinosa *and Chromatography of the Extract*.—Finely ground pods of *Caesalpinia spinosa* (40 g.) were shaken for 24 hr. with water (500 c.c.). Filtration, removal of water at 30°, and freeze-drying of the residue gave the tara extract (21—24 g.) as a buff solid. Its paper chromatography is recorded in Table 6. Quinic and shikimic acid were revealed with a spray of sodium metaperiodate followed by sodium nitroprusside and piperazine.[29]

The extract (10 g.) was dissolved in ethyl methyl ketone saturated with water (1 : 1), and this solution extracted 9 times with water saturated with the ketone (1·5 l. in all). The ketone

[29] Cartwright and Roberts, *Chem. and Ind.*, 1955, 231.

XUM

phase was evaporated to 50 c.c., water added, the whole evaporated, and the residue freeze-dried from water to give *tara tannin* (0·95—1·05 g.) as an off-white powder (Found: C, 52·0; H, 4·0. $C_{35}H_{28}O_{22}$ requires C, 52·5; H, 3·5%), R_F (*a*) 0·03—0·24, (*b*) 0·46—0·67.

Isolation of Gallic and Quinic Acid from Tara Tannin.—A mixture of tara tannin (1 g.) and 3N-hydrochloric acid (67 c.c.) was heated at 100° for 8½ hr., the solution becoming dark brown. After filtration, the solution was extracted with ether (10 × 70 c.c.). The extracts yielded

TABLE 6.

Spot	R_F (*a*)	R_F (*b*)	Spray (*a*)	U.v.–NH_3	Substance
(I)	0·02	0·28—0·41	—	Blue-green	Ellagic acid
(II)	0·02—0·37	0·35—0·50	+	Absorbs	Tara tannin
(III)	0·17	0·70	+	Blue-violet	Trigallic acid?
(IV)	0·29	0·69	+	Blue-violet	*m*-Digallic acid
(V)	0·20—0·39	0·30—0·40	+	Violet	Unknown
(VI)	0·45	0·66	+	Blue-violet	Gallic acid
(VII)	0·47	0·45	+	Absorbs	Unknown
(VIII)	0·49	0·35	+	Absorbs	Unknown
(IX)	0·64	0·40	+	Violet	Unknown
(X)	0·64	0·52	—	Green	Unknown
(XI)	0·64	0·66	—	Green	Unknown
(XII)	0·66—0·78	0·33	+	Violet	Unknown
(XIII)	0·70	0·75	—	Blue	Unknown
(XIV)	0·72	0·58	—	Green	Unknown
(XV)	0·75	0·70	—	Blue	Unknown
(XVI)	0·83	0·48	—	—	Shikimic acid
(XVII)	0·84	0·18	—	—	Quinic acid
(XVIII)	0·96	0·10	—	—	Carbohydrates

crude gallic acid (0·75 g.) which crystallised from water in needles, m. p. and mixed m. p. 240° (decomp.), and on treatment with excess of ethereal diazomethane in acetone afforded methyl 3,4,5-tri-*O*-methylgallate, m. p. and mixed m. p. 80°. The aqueous solution, after ether-extraction, was evaporated at 30°, diluted with water, and re-evaporated to remove all the hydrochloric acid. The residue was dissolved in water (25 c.c.) and filtered through charcoal (3 × 3 cm.) to remove residual polyphenols. After washing of the charcoal with water, the filtrate and washings were combined, concentrated at 30° to 20 c.c., and applied to a column of Dowex "2" (acetate form; 40 × 1 cm.). The column was washed with water (75 c.c.) and successive portions (100 c.c.) of 0·2N-, 0·5N-, N-, 2N-, and 4N-acetic acid, and each eluted fraction (100 c.c.) was concentrated to 10 c.c. and tested for quinic acid.[29] Evaporation at 30° of the 2N-eluate gave quinic acid (0·11 g.), which crystallised from ethanol in prisms, m. p. and mixed m. p. 174—175° (Found: C, 44·0; H, 6·4. Calc. for $C_7H_{12}O_6$: C, 43·8; H, 6·3%). This acid had an infrared spectrum identical with authentic quinic acid and on treatment with acetic anhydride [30] gave triacetylquinide, m. p. and mixed m. p. 133—134°.

Determination of Gallic Acid in Tara Tannin.—Gallic acid was determined as in Chinese or sumach gallotannin by measurement of (*a*) the optical density at 280 mμ after hydrolysis with tannase or (*b*) the alkali consumed during hydrolysis by tannase [Found: (*a*) 86·9, 87·8; (*b*) 83·0, 83·7%).

Determination of the Equivalent Weight of Tara Tannin.—Titration of mixtures of quinic acid and β-glucogallin (1 : 4) indicated that titration of the carboxyl group of quinic acid in presence of the gallate ion was complete at pH 5·4 at 37° or at pH 5·8 at 20°. Tara tannin (0·016 g.) was dissolved in water (10 c.c.), and aliquot parts (2 c.c.) were titrated with 0·05N-sodium hydroxide (Found: equiv., 873).

We thank the Department of Scientific and Industrial Research for a postgraduate fellowship to J. W. G. and for a maintenance grant to K. J.; the University for a Henry Ellison fellowship and E. H. Linley scholarship to H. J. R. and G. S. B. respectively; the Leverhulme Trust and Thos. Hedley & Co. for fellowships to T. S. and R. A. respectively; and Dr. R. O. B. Wijisekera who made some preliminary experiments on the synthesis of pentagalloylglucose. We also thank Miss M. A. McKinnon, B.A., and Miss V. Dufty of the microanalytical laboratory of this Department for extremely valuable work in the microanalysis of the hygroscopic materials.

THE UNIVERSITY, SHEFFIELD. [*Received, November 9th*, 1960.]

[30] Erwig and Koenigs, *Ber.*, 1889, **22**, 1459.

XUM

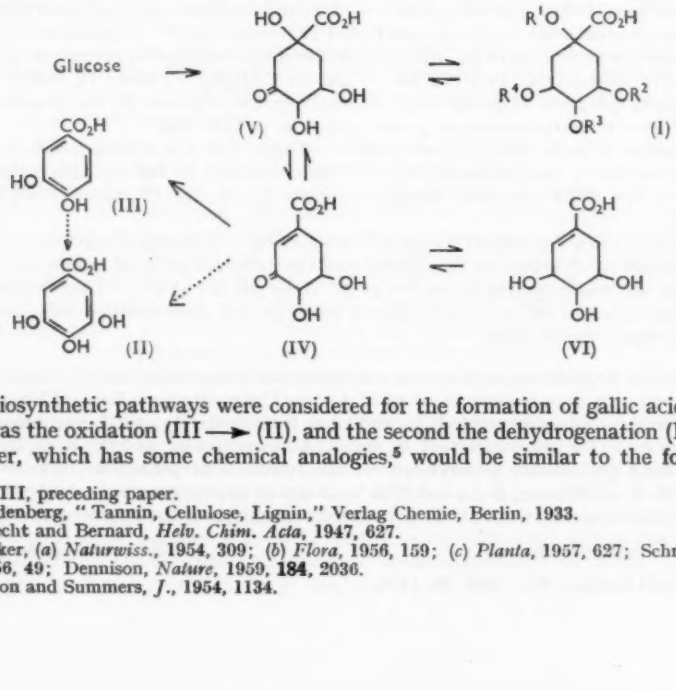
361. *Gallotannins. Part IV.*[1] *The Biosynthesis of Gallic Acid.*

By E. Haslam, R. D. Haworth, and P. F. Knowles.

The biosynthesis of gallic and protocatechuic acid from glucose in the mould *Phycomyces blakesleeanus* has been confirmed but it is unlikely that the former arises by oxidation of the latter acid. Qualitative and quantitative results indicate that the gallic acid is produced from glucose by a scheme similar to that suggested by Davis for the biosynthesis of aromatic amino-acids, but with 5-dehydroshikimic acid as the immediate precursor.

Our interest in the biosynthesis of gallic acid was stimulated by observations[1] on the tannin from the pods of *Caesalpinia spinosa* which showed it to have a galloylated quinic acid structure (I; R^1, R^2, R^3, R^4 = galloyl or polygalloyl), instead of the more usual galloylated glucose structure of the gallotannins from Chinese and Turkish galls and sumach leaves.[2] The co-occurrence of quinic (I; R's = H), and gallic acid (II) in the form of a gallotannin suggested that the former might be the biological precursor of gallic acid, and accordingly we have traced the route of biosynthesis of gallic acid in the mould *Phycomyces blakesleeanus* as a preliminary to the study of its biosynthesis and that of gallotannins in plants.

Several workers[3,4] have reported the formation of gallic acid by *Phycomyces blakesleeanus* when grown on glucose media, and Albrecht and Bernard[3] have isolated both this acid and protocatechuic acid (III) from old cultures of the mould. These reports have been confirmed, and the presence of gallic acid in the culture media was demonstrated by paper chromatography after 6—8 days' growth of the mould on glucose media; quantitative measurements indicated at this stage a concentration of 17 μg. of gallic acid per c.c. Both gallic and protocatechuic acid were isolated by counter-current distribution from cultures grown for 56 days, and the presence also of pyrogallol and catechol in these cultures was shown by paper chromatography, though these were not isolated.



Two biosynthetic pathways were considered for the formation of gallic acid; the first of these was the oxidation (III ⟶ (II), and the second the dehydrogenation (IV ⟶ II). The former, which has some chemical analogies,[5] would be similar to the formation of

[1] Part III, preceding paper.
[2] Freudenberg, "Tannin, Cellulose, Lignin," Verlag Chemie, Berlin, 1933.
[3] Albrecht and Bernard, *Helv. Chim. Acta*, 1947, 627.
[4] Brucker, (*a*) *Naturwiss.*, 1954, 309; (*b*) *Flora*, 1956, 159; (*c*) *Planta*, 1957, 627; Schroter, *Kultur pflanze*, 1956, 49; Dennison, *Nature*, 1959, **184**, 2036.
[5] Loudon and Summers, *J.*, 1954, 1134.

protocatechuic acid (III) itself from *p*-hydroxybenzoic acid as observed in *pseudomonas*.[6] However, it is unlikely that this mechanism is responsible for the biogenesis of gallic acid in *Phycomyces blakesleeanus* as the growth of the mould on a glucose medium containing small amounts of [^{14}C]protocatechuic acid did not give any isotopically labelled gallic acid. (The generally labelled [^{14}C]protocatechuic acid was prepared from [^{14}C]quinic acid obtained by the growth of roses in an atmosphere of [^{14}C]carbon dioxide, as described by Weinstein, Porter, and Laurencot.[7] Oxidation of the quinic acid with platinum and oxygen gave good yields of 5-dehydroquinic acid (V) which was quantitatively converted into protocatechuic acid with hydrochloric acid.[8])

Experiments with the widely distributed plant enzyme tyrosinase, which it is believed possesses the ability to bring about the insertion of a new hydroxyl group in the *ortho*-position to the one already present in a monohydric phenol,[9] indicated its inability to effect the conversion of protocatechuic acid into gallic acid and it is therefore concluded that oxidation of protocatechuic acid is not the mode of biogenesis of gallic acid.

The second route of biosynthesis involved the dehydrogenation of 5-dehydroshikimic acid (IV), one of the intermediate products in Davis's scheme[10] for the biosynthesis

FIG. 1. *Production of gallic acid from media containing* (A) *glucose, or glucose plus* (B) *shikimic acid,* (C) *5-dehydroquinic acid, or* (D) *5-dehydroshikimic acid.*

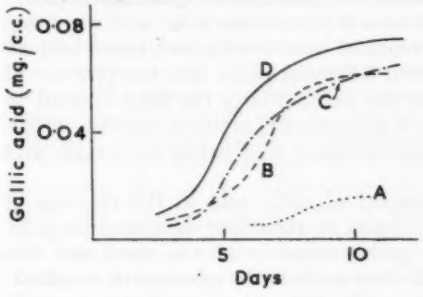
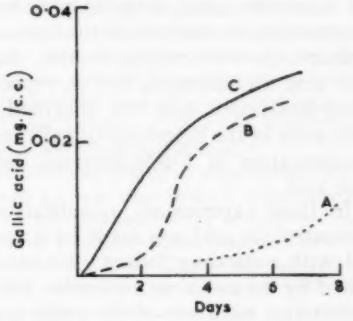


FIG. 2. *Production of gallic acid in replacement experiments from media containing* (A) *glucose,* (B) *5-dehydroquinic acid, or* (C) *dehydroshikimic acid.*



of aromatic amino-acids. Several workers[11,12] have shown that protocatechuic acid is formed in micro-organisms by dehydration of 5-dehydroshikimic acid (IV) and Gross,[11] using isotopically labelled precursors, has shown that this proceeds by elimination of the 3-hydroxyl group. The derivation of gallic acid by dehydrogenation of the same intermediate product (IV), followed by enolisation, was equally plausible. In support, 5-dehydroshikimic acid (IV) is oxidised to gallic acid by aeration in alkaline solution or, in good yield, by the action of Fehling's solution. In addition both 5-dehydroshikimic (IV) and shikimic acid (VI) were isolated from old cultures of *Phycomyces blakesleeanus* by ion-exchange chromatography, thus showing that this route of biosynthesis was operative in the mould. Final proof that 5-dehydroshikimic acid is the immediate precursor of gallic acid in *Phycomyces blakesleeanus* was derived from growth experiments. The mould was grown on glucose media which had been separately supplemented with one of the possible precursors quinic (I; R's = H), shikimic (VI), 5-dehydroquinic (V), and

[6] Evans, *Biochem. J.*, 1947, **41**, 373.
[7] Weinstein, Porter, and Laurencot, *Contrib. Boyce Thompson Inst.*, 1959, **20**, 121.
[8] Davis and Salomon, *J. Amer. Chem. Soc.*, 1953, **75**, 5567.
[9] Dawson and Tarpley, "The Enzymes," Academic Press Inc., New York, 1951, Vol. II, p. 460.
[10] Davis, "A Symposium on Amino-acid Metabolism," Johns Hopkins, Baltimore, 1956.
[11] Gross, *J. Biol. Chem.*, 1958, **233**, 1146.
[12] Tatum, *Proc. Nat. Acad. Science (U.S.)*, 1954, **40**, 271.

XUM

5-dehydroshikimic acid (IV), and the production of gallic acid followed quantitatively in each medium. When formation of gallic acid by the mould grown on glucose was taken as standard, increased production was observed (Fig. 1) in glucose media supplemented with shikimic, 5-dehydroquinic, or 5-dehydroshikimic acid, that with the last being greatest. The mould did not incorporate quinic acid. The pH of the media during these experiments was in the range 3—4 and the possibility of chemical transformation of the intermediates under these conditions was excluded by finding that no gallic acid was formed with media not subject to the action of the mould. The differing rates of formation of gallic acid in the different media were not attributable to differing rates of growth of the mould since the dry weights of mycelia grown in these ways were the same.

Further growth experiments were made by the medium-replacement technique,[13] since cell-free extracts of the enzymes in the mould could not be obtained. *Phycomyces blakesleeanus* was grown on glucose media for 12 days, whereby formation of gallic acid was established, and the media were then replaced, with little change in pH, by glucose media to which were added one of the possible precursors quinic, shikimic, 5-dehydroquinic, and 5-dehydroshikimic acid. Immediate resumption of the production of gallic acid was observed (Fig. 2) with media containing 5-dehydroshikimic acid, but with the other intermediates a period of induction (36 hr. for 5-dehydroquinic acid and 5 days for glucose alone) was observed before the formation of gallic acid was again detected, thus confirming the rôle of 5-dehydroshikimic acid as the direct precursor of gallic acid, and of shikimic and 5-dehydroquinic acids as near but not immediate precursors. Qualitative paper-chromatographic analysis of the replaced media after 3 days, when gallic acid was being produced, gave interesting results; in media replaced with 5-dehydroshikimic acid no other acid was detected, but on replacement with 5-dehydroquinic acid the presence of 5-dehydroshikimic acid was discerned. This further substantiates the rôles allotted to these acids in the biogenesis of gallic acid, since it indicates the probable necessity of the transformation of 5-dehydroquinic into 5-dehydroshikimic acid before conversion into gallic acid.

In these experiments, quantitative measurement of gallic acid in the presence of protocatechuic acid was made by a new method based on the colour developed by gallic acid with potassium iodate. Interference by protocatechuic acid was small and was limited by the use of an equimolar mixture of the two acids as the colorimetric standard: quantitative measures of the gallic acid present in 30—70% mixtures of the two acids were obtained.

Experimental

Paper Chromatography.—(1) *Phenols.* Whatman No. 1 paper was employed with the solvent systems (A) butan-1-ol–acetic acid–water (4 : 1 : 5), (B) aqueous acetic acid (6%), and (C) butan-2-ol–acetic acid–water (14 : 1 : 5). Two-dimensional chromatograms were prepared in solvent systems B and C. A ferric chloride–potassium ferricyanide spray[14] revealed the *o*-dihydroxyphenols as blue spots on a white background. The R_F values of the components in the solvent systems A, B, and C were: gallic acid 0·68, 0·52, 0·63; protocatechuic acid 0·85, 0·61, 0·75; pyrogallol 0·77, 0·76, 0·76; and catechol 0·91, 0·85, 0·91.

(2) *Cyclohexane acids.* Whatman No. 1 paper was employed with the solvent, benzyl alcohol–t-butyl alcohol–propan-2-ol–water (3 : 1 : 1 : 1) containing 2% of 90% formic acid. The R_F values of the acids were: quinic 0·22, shikimic 0·40, 5-dehydroquinic 0·25, and 5-dehydroshikimic 0·52. The acids were indicated with sprays of (*a*) Bromocresol Green, (*b*) sodium metaperiodate, sodium nitroprusside, and piperazine[15] or (*c*) sodium metaperiodate and aniline.[16] The colours developed with these reagents (*a*), (*b*), (*c*) were: quinic yellow, yellow, pink; shikimic yellow, yellow, red; 5-dehydroquinic yellow, brown, yellow; and 5-dehydroshikimic yellow, brown, yellow-green.

[13] Evans, *Ann. Reports*, 1956, **53**, 282.
[14] Kirby, Knowles, and White, *J. Soc. Leather Trades' Chemists*, 1953, **37**, 283.
[15] Cartwright and Roberts, *Chem. and Ind.*, 1955, 231.
[16] Yoshida and Hasegawa, *Arch. Biochem.*, 1957, **70**, 377.

Culture of Phycomyces blakesleeanus.—*Phycomyces blakesleeanus* was grown at 25° in full light. The culture medium recommended by Schöpfer [17] was used and contained glucose 10%, L-asparagine 0·2%, magnesium sulphate 0·05%, potassium dihydrogen phosphate 0·15%, and aneurin 0·025%.

Isolation from Culture Media.—(1) *Gallic and protocatechuic acid. Phycomyces blakesleeanus* was grown on Schöpfer medium (10 l.) for 56 days in full light, then the culture was separated from the mycelia by filtration and the mycelia were crushed with water (2 l.) in a Kenwood mixer. The combined aqueous extract and culture medium were reduced to 1 l. by rotary evaporation at 30° and passed through ZeoKarb 215 (40 × 4 cm.) to remove cations. Extraction with ether (10 × 250 c.c.) and evaporation gave a gum (0·94 g.) which paper chromatography showed to contain pyrogallol, catechol, and gallic and protocatechuic acid. The gum was subjected to a 75-tube counter-current distribution between ether and water. Concentration of fractions 18—24 gave gallic acid (0·12 g.) which crystallised from water in needles, m. p. and mixed m. p. 234—236°. Concentration of fractions 39—47 gave protocatechuic acid (0·08 g.) which crystallised from water in prisms, m. p. and mixed m. p. 195—196°.

(2) *Shikimic and 5-dehydroshikimic acid.* The aqueous solution obtained on removal of the phenolic acids by ether was concentrated at 30° to 500 c.c. and the water-soluble acids were removed by passage down Amberlite C.G. 400 (40 × 6 cm.; acetate form). The column was washed with water (10 × 1 l.) to remove traces of non-acidic material, and the acids were then eluted with 6N-acetic acid (3 × 1 l.). The acetic acid was removed from the eluate by evaporation at 30°, and the acids were re-adsorbed on a further column of Amberlite C.G. 400 (20 × 6 cm.) and eluted by gradient elution from a reservoir containing 6N-acetic acid (2 l.) and a mixing chamber containing 0·5N-acetic acid (500 c.c.). 150 Fractions of 10 c.c. were collected at the rate of 4 an hour and every fifth fraction was analysed by paper chromatography. Concentration of fractions 20—30 gave shikimic acid (0·20 g.) as a gum (methyl ester, m. p. and mixed m. p. 116—117°). 5-Dehydroshikimic acid was isolated from fractions 76—87 as a gum (0·10 g.) which after freeze-drying crystallised in needles (from ethyl acetate), m. p. and mixed m. p. 139—141° (Found: C, 49·0; H, 4·9. Calc. for $C_7H_8O_5$: C, 48·8; H, 4·7%), whose infrared spectrum was identical with that of authentic 5-dehydroshikimic acid.[18]

Oxidation of 5-Dehydroshikimic Acid.—Fehling's solution was prepared with sodium acetate sufficient to give pH 7. 5-Dehydroshikimic acid (0·10 g.) was dissolved in 0·2M-phosphate buffer (pH 8), and Fehling's solution added until no further precipitate of cuprous oxide appeared (2·0 c.c.). The solution was then acidified with 2N-hydrochloric acid and extracted with ethyl acetate (4 × 20 c.c.), and the extract dried ($CaSO_4$). Paper chromatography indicated the presence of large amounts of gallic and traces of protocatechuic acid. The former was isolated by counter-current distribution between ether and water as described above, and obtained as needles (0·075 g.), m. p. and mixed m. p. 236—240°.

Oxidations with Tyrosinase.—Samples of tyrosinase were prepared by the method of Mallette *et al.*[19] from the expressed juices of potato. The enzyme activity was tested with *p*-cresol and catechol.

The substance (1 mg.) was dissolved in a mixture of 0·1M-citric acid (2·5 c.c.) and 0·2M-disodium hydrogen phosphate (2·5 c.c.), and tyrosinase solution was added. Solutions were analysed after 1, 2, 3, 6, and 18 hr. After acidification with 2N-hydrochloric acid and extraction with ether, the extract was examined for phenolic material by paper chromatography. *p*-Hydroxybenzoic acid thus treated gave protocatechuic acid, but the latter acting as substrate gave no gallic acid.

Preparation of [^{14}C]*Quinic Acid* (cf. Weinstein, Porter, and Laurencot [7]).—Freshly cut, partially open, roses of the variety Lydia were placed in water in a bell-jar (4 × 1 l.) which was then partially evacuated. [^{14}C]Carbon dioxide was liberated in the bell-jar by the action of lactic acid (1 c.c.) on [^{14}C]barium carbonate (50 mg.). The jar was placed in full light and illuminated during periods of darkness with two 100-w electric bulbs, the temperature being kept below 28°. When the rose blooms had fully opened (3—4 days) the apparatus was evacuated once more, and the leaves and blooms (10 g.) were ground with crushed glass and water (5 × 200 c.c.). The aqueous extract was centrifuged and passed through a column of ZeoKarb 215(H^+), and the water-soluble organic acids were adsorbed on Amberlite C.G. 400 (3 × 4 cm.; acetate

[17] Schöpfer, *Arch. Mikrobiol.*, 1934, **5**, 511.
[18] Grewe and Jeschke, *Chem. Ber.*, 1956, **89**, 2080.
[19] Mallette, Lewis, Ames, Nelson, and Dawson, *Arch. Biochem.*, 1948, **16**, 288.

XUM

form). After washing of the column with water (1000 c.c.), the acids were removed by gradient elution from a mixing chamber containing 0·5N-acetic acid (400 c.c.) and a reservoir containing 4N-acetic acid (1 l.). Sixty fractions (10 c.c.) were collected, every third fraction was examined by paper chromatography, and those containing quinic acid were combined and concentrated at 30° to yield a colourless gum which crystallised from ethanol. Further crystallisation from ethanol gave [^{14}C]quinic acid (0·13 g.) as prisms, m. p. and mixed m. p. 173—174°. The specific activity, counted with a gas-flow Geiger–Müller tube, was 7200 counts min.$^{-1}$ mg.$^{-1}$.

[^{14}C]-5-*Dehydroquinic Acid*.—A solution of [^{14}C]quinic acid (0·12 g.) in water (20 c.c.) was adjusted to pH 6 with solid sodium hydrogen carbonate. Platinum (0·1 g.), freshly prepared by hydrogenation of platinum oxide, was added and a brisk stream of oxygen passed through the solution at 40° for 6 hr. The solution was filtered and passed through ZeoKarb 215 and then Amberlite C.G. 400 (10 × 15 cm., acetate form). The acids were removed by gradient elution with acetic acid, and 80 fractions (7·5 c.c.) collected and analysed by paper chromatography. Concentration of the appropriate fractions gave [^{14}C]-5-dehydroquinic acid (0·08 g.) as an oil which crystallised from acetone. Further crystallisation from acetone–chloroform gave needles, m. p. and mixed m. p. 136—138° (Found: C, 44·2; H, 5·7. Calc. for $C_7H_{10}O_6$: C, 44·2; H, 5·3%).

[^{14}C]*Protocatechuic acid*.—[^{14}C]Protocatechuic acid was prepared as described by Davis [8] by heating [^{14}C]-5-dehydroquinic acid with concentrated hydrochloric acid.

Growth of Phycomyces blakesleeanus *with* [^{14}C]*Protocatechuic Acid*.—*Phycomyces blakesleeanus* was grown on Schöpfer media (25 c.c.) containing [^{14}C]protocatechuic acid (8 mg.), and the culture medium was examined after 10 days by paper chromatography. No [^{14}C]gallic acid was detected on the chromatogram by autoradiographic analysis.

Determination of Gallic Acid.—The solution investigated (1, 2, 3, or 4 c.c.) was diluted to about 9 c.c., treated with 0·04M-potassium iodate (0·5 c.c.) and made up to 10 c.c. with water. After 4 hr. at room temperature the colour was measured at 500 mμ on a Unicam S.P. 500 spectrophotometer. The results were plotted and compared with those for a standard gallic acid solution (~10^{-3}M). Three different solutions gave (*a*) 8·0, 7·8, (*b*) 10·3, 10·2, and (*c*) 11·8, 12·1, the theoretical values being (*a*) 8·2, (*b*) 10·6, and (*c*) 12·0 mg./c.c. respectively. In the presence of protocatechuic acid, analysis was carried out with a standard solution containing equimolar amounts of gallic and protocatechuic acid. Four synthetic mixtures of gallic and protocatechuic acid, containing 75, 66·6, 33·3, and 25% of gallic acid severally, gave (*a*) 13·0, 12·7, (*b*) 14·0, 13·8, 13·9, (*c*) 11·6, 11·3, 11·9, and (*d*) 10·2, 10·4, and 10·1, and the theoretical values being (*a*) 11·9, (*b*) 13·3, (*c*) 12·0, and (*d*) 11·3 mg./100 c.c. respectively.

Growth of Phycomyces blakesleeanus *on Mixtures of Glucose and the Substrates* (I, IV, V, VI).—Four aqueous solutions (90 c.c.) containing glucose (9·0 g.) and one of the substrates quinic (I; R's = H), 5-dehydroquinic (V), shikimic (VI), and 5-dehydroshikimic acid (VI) (0·9 g.) were sterilised by filtration through "steripads." Standard sterilised Schöpfer medium (90 c.c.) from which the glucose had been omitted was added to each of these solutions and after inoculation with flooded *Phycomyces blakesleeanus* culture (3 c.c.) the mixtures were divided into thirty-six portions (5 c.c.), which were incubated in small flasks (25 c.c.) at 25° in full light. The solutions were analysed for gallic acid after 2, 4, 6, 8, 10, and 12 days, three solutions being taken for each substrate and the average of the values plotted. Mycelia were separated by filtration and washed with water (1 c.c.), and the filtrate and washings were combined and made up to 9·5 c.c. with 0·5M-acetate buffer (pH 4·0). The optical density of this solution was measured at 500 mμ, and 0·04M-potassium iodate (0·5 c.c.) was added. After 4 hr. the optical density was measured and the gallic acid content was determined by comparison with a standard gallic acid solution as indicated above. The results are plotted in Fig. 1. The weights of dried mycelia produced by each solution were determined after 6 and 12 days, but no significant differences were observed for the different substrates. Experiments in which the different media were left for 12 days without inoculation produced no gallic acid.

Replacement Experiments.—(1) *Qualitative analysis*. Four standard Schöpfer media (20 c.c.) were inoculated and incubated at 25°. After 12 days the medium was removed with a sterile pipette, and the mycelium washed with sterile water (2 × 10 c.c.) and placed in contact with a standard Schöpfer medium (20 c.c.) containing one of the substrates quinic, 5-dehydroquinic, shikimic, and 5-dehydroshikimic acid (0·20 g.). Incubation was continued for a further 3 days, then the mycelia were separated and the aqueous filtrate passed down a column of ZeoKarb

215 (1 × 20 cm.). Ether-extracts (4 × 50 c.c.) of the eluates were analysed by paper chromatography for phenolic material. The aqueous layer was concentrated at 30° and analysed similarly by paper chromatography.

(2) *Quantitative analysis.* Standard Schöpfer media (5 c.c.) were incubated at 25° for 12 days, and the media removed under the sterile conditions described above. Replacements were carried out with standard Schöpfer media (5 c.c.) sterilised by filtration and containing one of the substrates quinic, shikimic, 5-dehydroquinic, and 5-dehydroshikimic acid (25 g.). Incubation was continued at 25° and the gallic acid content of the replaced media analysed after 1, 2, 4, 6, and 8 days. The solutions were analysed for each substrate, with the results shown in Fig. 2.

The authors acknowledge many helpful discussions with Professor S. R. Elsden. They also thank the Department of Scientific and Industrial Research for a maintenance grant to P. F. K.

THE UNIVERSITY, SHEFFIELD. [*Received, November 9th,* 1960.]

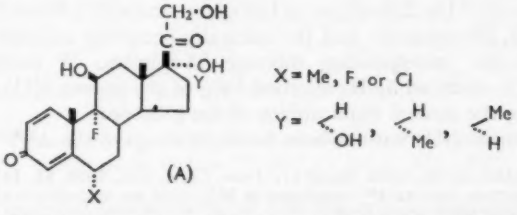
---

362. *Steroidal Sapogenins. Part XL.* Reaction of 12-Oxo-sapogenins with Selenium Dioxide: Synthesis of 3β-Hydroxypregna-5,9(11),16-trien-20-one from Botogenin.*

By A. BOWERS, E. DENOT, MARIA BLANCA SANCHEZ, F. NEUMANN, and CARL DJERASSI.

Selenium dioxide dehydrogenates botogenin or its acetate to 9,11-dehydro-derivative, thus proving the stability (previously denied) of the spiroketal system to this reagent. An alternative four-step dehydrogenation of the acetate is also described. The dehydro-derivative has been degraded to 3β-acetoxypregna-5,9(11),16-trien-20-one.

FROM much recent work it has emerged that compounds of type (A) will, in general, have high biological anti-inflammatory activity without sodium retention; consequently any intermediate that can afford a compound of this type might find wide application. From this standpoint 3β-acetoxypregna-5,9(11),16-trien-20-one (VI) appears useful since the requisite substitution at positions 6, 9(11), and 16 should be possible in view of the unsaturation present and widely differing reactivity of the three double bonds. This paper reports the preparation of compound (VI) from the naturally occurring botogenin (12-oxodiosgenin) [1] (I).



Previous work [2,3] with botogenin (and its 25-epimer) has been directed towards moving the 12-keto-function to position 11, and both 11-oxo- and 11α-hydroxy-diosgenin have

* Part XXXIX, *J. Org. Chem.*, in the press.

[1] (*a*) Marker and Lopez, *J. Amer. Chem. Soc.*, 1947, **69**, 2397; (*b*) Walens, Serota, and Wall, *ibid.*, 1955, **77**, 5196; *J. Org. Chem.*, 1957, **22**, 182.

[2] Rothman and Wall, *J. Amer. Chem. Soc.*, 1957, **79**, 3228; *J. Org. Chem.*, 1958, **23**, 1741; Halpern and Djerassi, *J. Amer. Chem. Soc.*, 1959, **81**, 439.

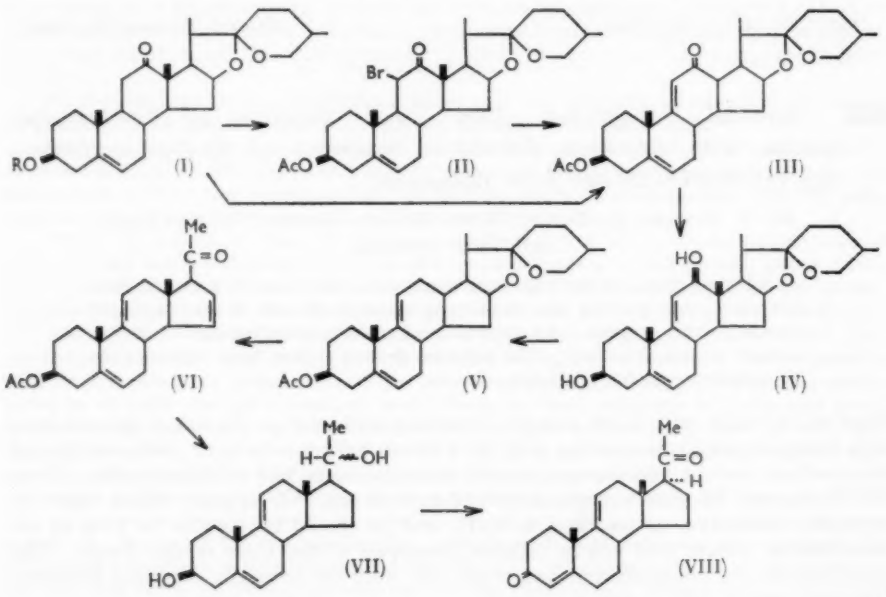
[3] Cf. Romo, *Bol. Inst. Quim. Mex.*, **7**, 1955, 53.

XUM

been described. The latter, in particular, would be a useful precursor [4] for 9(11)-dehydrodiosgenin (V), but the multi-stage conversion of botogenin (I) into 11α-hydroxydiosgenin made a more direct route to 9(11)-dehydrodiosgenin desirable.

Rothman and Wall [2] prepared the 11,23-dibromide (II) by a two-stage sequence from botogenin acetate (I; R = Ac), and dehydrobromination of this with collidine followed by reductive removal of the 23-bromine atom with zinc led to the $\Delta^{9(11)}$-12-ketone (III) in 19% overall yield from botogenin acetate.

In the bile acid series it is known that 12-ketones can be oxidized to $\Delta^{9(11)}$-12-ketones by selenium dioxide [5] in the presence of acetic acid but reports [6] about the instability of the spiroketal system to selenium dioxide have discouraged its use with steroidal sapogenins. However, we find that botogenin acetate and selenium dioxide in t-butyl alcohol containing some pyridine give a 70% yield of the $\Delta^{9(11)}$-12-ketone (III; 25a-epimer [7]).*



Similarly, correllogenin [1b] the 25b-epimer of botogenin smoothly afforded the corresponding $\Delta^{9(11)}$-12-ketone (III, 25b-epimer); and the naturally occurring mixture of botogenin and correllogenin gave the corresponding mixture 25-epimers. A similar reaction with hecogenin acetate (I; reduced 5α-H) afforded 89% of the known 9(11)-dehydrohecogenin acetate,[8] illustrating the general applicability of the procedure.

Reducing compound (III) with sodium borohydride gave the $\Delta^{5,9(11)}$-3β,12β-diol (IV),

* After the completion of this work Mazur (*J. Amer. Chem. Soc.*, 1959, **81**, 1454) reported the conversion of hecogenin acetate into its $\Delta^{9(11)}$-analogue in 36% yield by oxidation with selenium dioxide in t-butyl alcohol containing some acetic acid.

[4] For the conversion of 11α-alcohols into 9(11)-unsaturated steroids see Fried and Sabo (*J. Amer. Chem. Soc.*, 1953, **75**, 2273), and Rosenkranz, Mancera, and Sondheimer (*ibid.*, 1954, **76**, 2227).

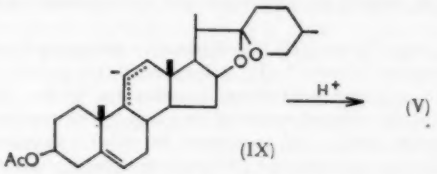
[5] Schwenk and Stahl, *Arch. Biochem.*, 1947, **14**, 125.

[6] Marker and Rohrmann, *J. Amer. Chem. Soc.*, 1939, **61**, 846; contrast Hirschmann, Snoddy, and Wendler (*ibid.*, 1953, **75**, 3252).

[7] For nomenclature of the side chain see Djerassi, Grossnickle, and High (*J. Amer. Chem. Soc.*, 1956, **78**, 3166, footnote 10; see also Lardon, Schindler, and Reichstein (*Helv. Chim. Acta*, 1957, **40**, 678), and Djerassi and Fishman (*J. Amer. Chem. Soc.*, 1955, **77**, 4291).

[8] Djerassi, Martinez, and Rosenkranz, *J. Org. Chem.*, 1951, **16**, 303.

whose diacetate, on treatment with lithium and ethylamine,[9] underwent hydrolysis of the 3β-acetate and reductive acetolysis of the allylic 12β-acetate, affording $^{9(11)}$-dehydrodiosgenin (V). Reductive elimination of allylic ethers or acetates takes place *via* a mesomeric carbanion,[9,10] in this case (IX); protonation of this intermediate is very probably a thermodynamically controlled process:* one may confidently assign the trisubstituted double-bond structure (V) rather than the disubstituted Δ^{11}-isomer* to the product. The sapogenin side chain of 9(11)-dehydrodiosgenin (V) was then degraded



by the standard Marker procedure,[11] to afford the desired 3β-acetoxypregna-5,9(11),16-trien-20-one (VI).

Lithium in liquid ammonia selectively reduced the Δ^{16}-double bond of this αβ-unsaturated ketone (VI). A mild alkali treatment to complete hydrolysis of the 3-acetate group, followed by an Oppenauer oxidation of the crude reduction product (VII), then afforded pregna-4,9(11)-diene-3,20-dione[12] (VIII). This sequence of reactions further established the correctness of the structure (VI).

Experimental

Rotations were determined for chloroform and ultraviolet light absorption spectra for 95% ethanol solutions. We are grateful to Dr. L. J. Throop and his staff for these measurements and for the infrared spectra which were obtained with a Perkin–Elmer model 21 spectrophotometer with a sodium chloride prism. The elemental analyses were carried out by Dr. A. Bernhardt, Mülheim/Ruhr, Germany.

$\Delta^{9(11)}$-*Dehydrobotogenin Acetate* [3-*Acetoxy*-22α,25a-*spirosta*-5,9(11)-*dien*-12-*one*] †† (III).—(a) *From the dibromide* (II). 3β-Acetoxy-11α,23-dibromo-22α,25a-spirost-5-en-12-one (II) (Halpern *et al.*[2]) (5·0 g.) in collidine (60 c.c.) was heated under reflux for 1 hr. The cooled solution was added to ice-water, and the product extracted with ether (4 × 200 c.c.). The combined ether solutions were washed successively with 2N-hydrochloric acid, 5% sodium hydrogen carbonate solution, and water. Removal of the ether *in vacuo* from the dried solution (Na_2SO_4) afforded a non-crystalline product (4·4 g.), $\lambda_{max.}$ 238—240 mμ (ε 6300). After the addition of zinc dust (28 g.) a solution of this crude product in ethanol (200 c.c.) was heated under reflux for 8 hr. Filtration and removal of the ethanol *in vacuo* gave a product which was adsorbed from benzene on alumina (250 g.). Elution with benzene (1200 c.c.) afforded $\Delta^{9(11)}$-*dehydrobotogenin acetate* (III) (1·46 g.), m. p. 180—190°, $\lambda_{max.}$ 238 mμ (ε 10,470), raised by several crystallisations from ethyl acetate–hexane to 196—197°, $[\alpha]_D$ −34°, $\lambda_{max.}$ 238 mμ (ε 11,750), $\nu_{max.}$ (in KBr) 1730, 1668, 1597, 1245, 983, 920, 902, and 865 cm.$^{-1}$ (Found: C, 74·6; H, 8·6; O, 16·8. $C_{29}H_{40}O_3$ requires C, 74·3; H, 8·6; O, 17·1%).

(b) *Oxidation of botogenin acetate* (I) *by selenium dioxide.* Selenium dioxide (45 g.) was added to a solution of botogenin acetate (I) (167 g.) (m. p. 215—220°, $[\alpha]_D$ −57°) in t-butyl

* A kinetically controlled protonation of our intermediate (IX) would probably lead to the same product since steric hindrance to the approach of a proton source is less at position 12(α) than at position 9(α).

†† The use of α and β to designate the stereochemistry at position 22 follows from the recommendations of the International Union of Pure and Applied Chemistry ("Nomenclature of Organic Chemistry, 1957," Butterworths Scientific Publications, London, 1958, p. 77.

[9] Hallsworth, Henbest, and Wrigley, *J.*, 1957, 1969.
[10] Birch, *Quart. Rev.*, 1950, **4**, 69.
[11] Marker and Rohrmann, *J. Amer. Chem. Soc.*, 1939, **61**, 3592; 1940, **62**, 518.
[12] Shoppee and Reichstein, *Helv. Chim. Acta*, 1941, **24**, 351.

XUM

alcohol (8 l.) containing pyridine (13·5 c.c.) and heated under reflux with stirring in an atmosphere of nitrogen for 24 hr. A further 45 g. of selenium dioxide and 13·5 c.c. of pyridine were then added and heating was continued under the same conditions for a further 72 hr. The cooled mixture was then filtered through Celite to remove the precipitated selenium and the solvent was then removed *in vacuo*. The solid residue was triturated with water (2 × 2·5 l.), filtered, and recrystallised from methanol (10 g. of charcoal), to afford $\Delta^{9(11)}$-dehydrobotogenin acetate (III) (117 g., 70%), m. p. 193—197°, raised by several recrystallisations from methanol to 201—202°, $[\alpha]_D$ −32°, $\lambda_{max.}$ 238 mμ (ε 11,480). The mixed m. p. with the product prepared as described in method (a) showed no depression and the infrared spectra of the two products were identical.

$\Delta^{9(11)}$-*Dehydrocorrellogenin Acetate* (III) (25*b*-*Epimer*).—Selenium dioxide (500 mg.) was added to a solution of correllogenin acetate * (I; 25*b*-epimer) (1·0 g.) in t-butyl alcohol (45 c.c.) containing pyridine (0·15 c.c.) and heated under reflux for 96 hr. The cooled mixture was filtered through Celite and the solvent removed *in vacuo*. The residue was dissolved in ethyl acetate, washed with water, dried, and recovered *in vacuo*. Crystallisation of the product from methylene dichloride–hexane afforded $\Delta^{9(11)}$-*dehydrocorrellogenin acetate* (III; 25b-epimer) (620 mg.), which after several crystallisations from methylene dichloride–hexane had m. p. 219—220°, $[\alpha]_D$ −42°, $\lambda_{max.}$ 238 mμ (ε 12,590), $\lambda_{max.}$ (in KBr) 1735, 1675, 1600, 1250, 985, 918, 896, and 850 cm.$^{-1}$ (Found: C, 73·9; H, 8·4. $C_{29}H_{40}O_5$ requires C, 74·3; H, 8·6%).

Oxidation of the acetate of the naturally occurring mixture of 25-epimers gave similarly a mixture of 25-epimers (65% yield), m. p. 190—196°, $[\alpha]_D$ −37°, $\lambda_{max.}$ 238 mμ (ε 11,960).

$\Delta^{9(11)}$-*Dehydrohecogenin Acetate* (III; 5α-H).—Selenium dioxide (27 g.) was heated with hecogenin acetate (I; 5α-H) (54 g.) in t-butyl alcohol (2·4 l.) containing pyridine (8·0 c.c.) as above. The cooled mixture was filtered on Celite and the solvent removed *in vacuo*. The residual solid was suspended in water (2 l.) with stirring for 15 min. Filtration afforded $\Delta^{9(11)}$-dehydrohecogenin acetate (III; 5α-H) (48·2 g., 89%) that after one crystallisation from methanol had m. p. 215—217°, $[\alpha]_D$ −9°, $\lambda_{max.}$ 238 mμ (ε 11,700) (lit.,[13] m. p. 218—220°, $[\alpha]_D$ −8·7°).

$\Delta^{5,9(11)}$-22α,25a-*Spirostadiene*-3β,12β-*diol* (IV).—Sodium borohydride (6·0 g.) in water (8·0 c.c.) was heated with $\Delta^{9(11)}$-botogenin acetate (III) (10·0 g.) in tetrahydrofuran (250 c.c.) for 3 hr. Addition of ice-water (1·5 l.) containing acetic acid (10 c.c.) and filtration afforded 22α,25a-spirosta-5,9(11)-diene-3β,12β-diol (IVa) (9·35 g.), m. p. 185—192°, raised by several crystallisations from benzene–hexane to 218—220°, $[\alpha]_D$ −107°. This diol had no selective ultraviolet absorption (Found: C, 76·0; H, 9·4; O, 14·7. $C_{27}H_{40}O_4$ requires C, 75·7; H, 9·4; O, 14·9%). With acetic anhydride in pyridine under reflux for 3 hr. it afforded 3β,12β-diacetoxy-22α,25a-spirosta-5,9(11)-diene, m. p. 191—193° (from methanol–chloroform), $[\alpha]_D$ −120° (Found: C, 72·4; H, 8·8; O, 18·8. $C_{31}H_{44}O_6$ requires C, 72·6; H, 8·7; O, 18·7%).

Treatment of 3β,12β-*Diacetoxy*-22α,25a-*spirosta*-5,9(11)-*diene with Lithium and Ethylamine*.—A solution of the diacetate (500 mg.) in ethylamine (20 c.c.) was added with stirring to a solution of lithium (125 mg.) in ethylamine (25 c.c.) at 5° and kept at this temperature for 20 min. Addition of solid ammonium chloride (5·0 g.), evaporation of the ethylamine, and addition of water afforded a solid precipitate which was removed and dried at 60°. Acetic anhydride (1·0 c.c.) was then added to a solution of this product in pyridine (7·0 c.c.). After 16 hr. at room temperature addition of water, filtration, and crystallisation of the solid product from acetone–hexane afforded 3β-acetoxy-22α,25a-spirosta-5,9(11)-diene (V) (310 mg.), m. p. 185—190° raised by further crystallisations to 196—197°, $[\alpha]_D$ −78° (Found: C, 76·6; H, 9·4; O, 14·0. $C_{29}H_{42}O_4$ requires C, 76·6; H, 9·3; O, 14·0%).

3-*Acetoxypregna*-5,9(11),16-*trien*-20-*one* (VI).—$\Delta^{9(11)}$-Dehydrodiosgenin acetate (V) (3·0 g.) in acetic anhydride (15 c.c.) was heated at 195° (vapour of nitrobenzene under reflux in Mexico, D.F.) in a sealed glass tube for 3 hr. The cooled solution was poured into ice-water, and the product isolated by extraction with ethyl acetate. The combined extracts were washed with 5% sodium carbonate solution and water and then dried (Na_2SO_4). Removal of the solvent *in vacuo* afforded a product which was dissolved in a mixture of acetic acid (47 c.c.), water (17·7 c.c.), and methylene dichloride (38 c.c.) and cooled to 0°. A solution of chromium

* Triangular fractional crystallisation of the acetates of the naturally occurring mixture of botogenin and correllogenin from ethyl acetate–hexane afforded pure correllogenin acetate, m. p. 213—215°, $[\alpha]_D$ −67°, characterized by infrared bands at 1728, 1698, 1240, 984, 916, 896, and 851 cm.$^{-1}$.

[13] Djerassi, Martinez, and Rosenkranz, *J. Org. Chem.*, 1951, **16**, 303.

trioxide (1·41 g.) in water (2·34 c.c.) and acetic acid (23·4 c.c.) was then added during 45 min. at 0° and the whole was stirred at room temperature for a further 2 hr. Addition of water and isolation with methylene dichloride afforded a product which was heated under reflux for 1 hr. in acetone (20 c.c.) and water (9 c.c.) containing potassium hydroxide (1·5 g.). Addition of ice-water and isolation with ether gave a product which was heated at 90° for 1 hr. in pyridine (20 c.c.) containing acetic anhydride (5·0 c.c.). The product from the acetylation was isolated by the addition of ice-water to the reaction mixture, followed by extraction with ether. The ether solution was washed free from pyridine with 2N-hydrochloric acid and water. Removal of the ether from the dried solution (Na_2SO_4) and crystallisation of the residue from hexane afforded 3-acetoxypregna-5,9(11),16-trien-20-one (VI) (1·35 g.), m. p. 160—163°, raised by several crystallisations from hexane to 170—172°, $[\alpha]_D$ +53°, $\lambda_{max.}$ 238—240 mμ (ε 8915) (Found: C, 77·8; H, 8·7. $C_{23}H_{30}O_3$ requires C, 77·9; H, 8·5%).

Conversion of the Ketone (VI) *into Pregna-4,9(11)-diene-3,20-dione* (VIII).—A solution of the product (VI) (500 mg.) in dry dioxan (40 c.c.) was added during 5 min. to one of lithium (500 mg.) in liquid ammonia (500 c.c.). The blue colour was discharged by solid ammonium chloride. After evaporation, addition of water and extraction with ethyl acetate afforded a product which was heated under reflux for 30 min. in methanol (50 c.c.) containing potassium hydroxide (1·0 g.). Neutralisation with acetic acid, removal of the bulk of the solvent on the steam-bath, and addition of water afforded a precipitate (400 mg.) which was collected and dried at 90°. A solution of this product in dry toluene (10 c.c.) containing cyclohexanone (2 c.c.) and aluminium isopropoxide (800 mg.) was heated under reflux for 25 min. Water (50 c.c.) was then added and the solution was distilled until the distillate was essentially free from toluene and cyclohexanone. Extraction of the residue with benzene afforded a product which was adsorbed from 1 : 1 benzene–hexane (50 c.c.) on alumina (15 g.). Elution with benzene (150 c.c.) and one crystallisation from benzene–methylene dichloride afforded the diketone (VIII) (130 mg.), m. p. 110—113°, raised by one further crystallisation to 119—120°, $[\alpha]_D$ +149° (lit., m. p. 122°, $[\alpha]_D$ +145°). The m. p. was undepressed on admixture with an authentic sample.

RESEARCH LABORATORIES, SYNTEX, S.A.
APARTADO POSTAL 2679, MEXICO, D.F.

[*Received, September 13th,* 1960.]

---

363. *The Chemotherapy of Schistosomiasis. Part IV.*[1] *Some Ethers of 4-Amino-2-methoxyphenol.*

By R. F. COLLINS and M. DAVIS.

Numerous alkyl and substituted alkyl ethers of 4-amino-2-methoxyphenol have been prepared, together with some related compounds and *N*-substituted derivatives. Many of the compounds are schistosomicides.

IN earlier parts of this series[1,2,3] we have reported alkyl and substituted alkyl ethers of *p*-aminophenol which were effective against *Schistosoma mansoni* infections.[4,5] Some of these compounds produced undesirable ocular effects in cats, but it was noted that this response, which was particularly marked with 1,5-di-(*p*-aminophenoxy)pentane, was absent with the *o,o'*-dimethoxy-derivative.[4] Many more ethers of 4-amino-2-methoxyphenol (4-aminoguaiacol) have therefore been synthesised and tested biologically,[6] the majority being alkyl ethers either unsubstituted or carrying substituents such as hydroxy, alkoxy, alkylthio, aryl, aryloxy, arylthio, arylsulphonyl, etc. For some of these compounds the effects of branching or unsaturation in the chain, and of substitution in the amino-group,

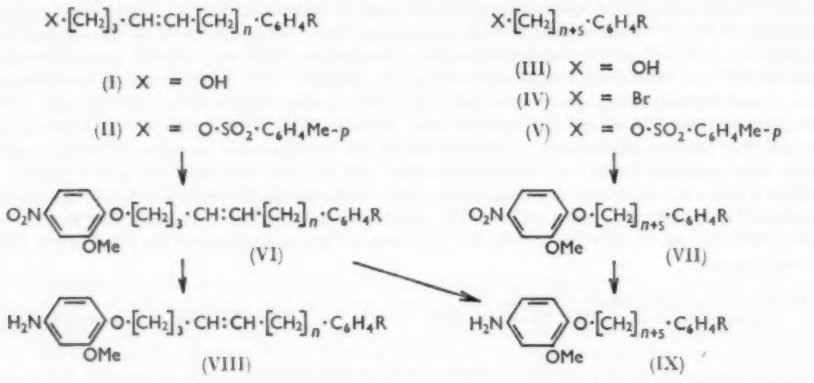
[1] Part III, Ashley, Collins, Davis, and Sirett, *J.*, 1959, 3880.
[2] Ashley, Collins, Davis, and Sirett, *J.*, 1958, 3298.
[3] Ashley, Collins, Davis, and Sirett, *J.*, 1959, 897.
[4] Collins, Davis, Edge, and Hill, *Brit. J. Pharmacol.*, 1958, **13**, 238.
[5] Collins, Davis, Edge, Hill, Reading, and Turnbull, *Brit. J. Pharmacol.*, 1959, **14**, 467.
[6] Collins, Davis, Edge, Hill, and Weston, unpublished work.

XUM

have been investigated and a few positional isomers and other related compounds, as well as some further ethers of *p*-aminophenol, have been prepared.

The general method of synthesis used was the condensation of potassium 2-methoxy-4-nitrophenoxide [7] (obtained almost quantitatively by refluxing 4-nitroveratrole with aqueous potassium hydroxide) with the appropriate chloride, bromide, or toluene-*p*-sulphonate, followed by reduction of the nitro-compound to the amine either catalytically or by using sodium sulphide. In some instances 4-acetamido-2-methoxyphenol [8] was used and the condensation product was hydrolysed with acid.

As a homologous series of ω-phenylalkyl halides was required for this work, the Crombie–Harper synthesis [9,10,11] using 2,3-dichlorotetrahydropyran and phenyl or phenylalkyl halides was employed and gave satisfactory overall yields of *trans*-ω-phenylalk-4-en-1-ols (Ia—e). Catalytic reduction afforded the corresponding saturated alcohols (IIIa—e) which were converted into the bromides (IVa—d) or, in one instance, into the toluene-*p*-sulphonate (Ve). Condensation with potassium 2-methoxy-4-nitrophenoxide yielded the



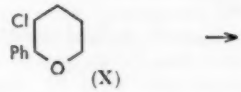
(a) $n = 0$, R = H, (b) $n = 1$—3, R = H, (c) $n = 0$, R = *o*-Me, (d) $n = 0$, R = *p*-Me, (e) $n = 0$, R = *p*-OMe.

nitro-compounds (VII) which were reduced catalytically to the amines (IX). In an alternative procedure, the phenylalkenols (Ia, d, and e) were converted into the toluene-*p*-sulphonates (IIa, d, and e) and thence into the unsaturated nitroguaiacyl ethers (VI), which were reduced either catalytically to the saturated amines (IX) or with sodium sulphide to the unsaturated amine (VIII).

4-Benzoylbutyl bromide (XII) was first prepared by Perkin [12] from benzoylacetic ester (XIII) and 1,3-dibromopropane, the intermediate ethyl 5,6-dihydro-2-phenyl-4*H*-pyran-3-carboxylate (XIV) being hydrolysed and decarboxylated to 3,4-dihydro-6-phenyl-2*H*-pyran (XI), which was then treated with hydrobromic acid. We have found that the key intermediate (XI) is formed in 78% yield by dehydrochlorination of the mixed *cis*- and *trans*-isomers of 3-chlorotetrahydro-2-phenylpyran [13] (X) with sodamide in boiling toluene. The absence of a double-bond isomer of (XI) was shown by almost quantitative conversion of the product into 4-benzoylbutyl bromide. Riobé [11] obtained a mixture of two isomers on heating 3-chlorotetrahydro-2-methylpyran with potassium hydroxide in ethylene glycol, the proportion depending on whether the *cis*- or *trans*-chloro-compound

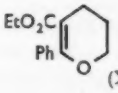
[7] Pollecoff and Robinson, *J.*, 1918, **113**, 645.
[8] Heidelberger and Jacobs, *J. Amer. Chem. Soc.*, 1919, **41**, 1450.
[9] Crombie and Harper, *J.*, 1950, 1707; Crombie, Gold, Harper, and Stokes, *J.*, 1956, 136.
[10] Ansell and Selleck, *J.*, 1956, 1238; Ansell and Thomas, *J.*, 1957, 3302.
[11] Riobé, *Ann. Chim.* (*France*), 1949, **4**, 630.
[12] Perkin, *J.*, 1887, **51**, 702; cf. Normant, *Compt. rend.*, 1950, **231**, 909; Montaigne, *Ann. Chim.* (*France*), 1954, **9**, 310.
[13] Paul, *Compt. rend.*, 1944, **218**, 122.

was used. Treatment of 3-bromo-2-ethyltetrahydropyran with sodamide in liquid ammonia has been investigated [14] as a route to hept-4-yn-1-ol. Two higher homologues of 4-benzoylbutyl bromide were prepared by a modification of Perkin's method. When benzoylacetic ester (XIII) was condensed with 4-*p*-methoxyphenoxybutyl bromide, and the intermediate ester (XVIIb) was subjected to ketonic hydrolysis, 1-benzoyl-5-*p*-methoxyphenoxypentane (XXb) was obtained; it was converted by aqueous hydrobromic acid



(X) →

(XI) → $Ph\cdot CO\cdot[CH_2]_4\cdot Br$ (XII)

$Ph\cdot CO\cdot CH_2\cdot CO_2Et$ (XIII) → 

(XIV) → $PhCH{:}CH\cdot[CH_2]_5\cdot R$ (XV)

↓

$Ph\cdot CO\cdot CH(CO_2Et)\cdot[CH_2]_n\cdot R$ $Ph\cdot CO\cdot[CH_2]_{n+1}\cdot R$ $Ph\cdot CH(OR')\cdot[CH_2]_{n+1}\cdot R$

(XVI) $n = 3$	(XIX) $n = 3$	(XXII) $n = 3$, $R' = H$
(XVII) $n = 4$	(XX) $n = 4$	(XXIII) $n = 3$, $R' = Ac$
(XVIII) $n = 5$	(XXI) $n = 5$	(XXIV) $n = 4$, $R' = H$
		(XXV) $n = 5$, $R' = H$
		(XXVI) $n = 5$, $R' = Ac$

R = (a) Br, (b) $O\cdot C_6H_4\cdot OMe$-*p*, (c) $O\cdot C_6H_4\cdot NO_2$-*p*, (d) $O\cdot C_6H_3(OMe)\cdot NO_2$-3,4.

into 5-benzoylpentyl bromide (XXa). Later, it was found that condensation of benzoylacetic ester with an excess of 1,5-dibromopentane and treatment of the crude product (XVIIIa) with hydrobromic acid yielded 6-benzoylhexyl bromide (XXIa) directly.

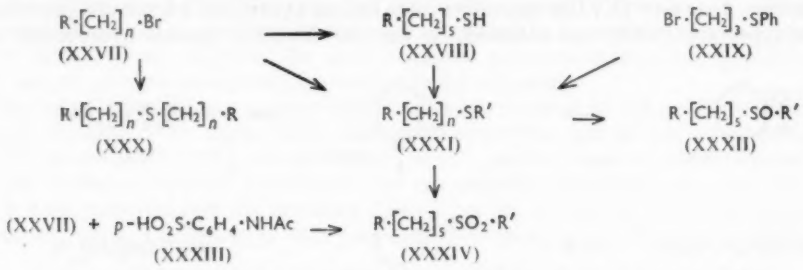
Reaction of the appropriate benzoylalkyl bromide with potassium 2-methoxy-4-nitrophenoxide or potassium *p*-nitrophenoxide afforded respectively the benzoyl alkyl ethers (XIXd), (XXId), (XIXc),[1] and (XXc). 4-Benzoyl-1-*p*-nitrophenoxybutane (XIXc) and 5-benzoyl-1-*p*-nitrophenoxypentane (XXc) were also obtained directly from benzoylacetic ester by condensation with 3-*p*-nitrophenoxypropyl bromide, or 4-*p*-nitrophenoxybutyl bromide, respectively, followed by alkaline hydrolysis of the intermediate esters (XVIc) and (XVIIc). Reduction of the nitro-ketones by the Meerwein–Ponndorf method, previously described [1] for the preparation of 5-*p*-nitrophenoxy-1-phenylpentane-1-ol (XXIIc), was employed for the nitro-alcohols (XXIId), (XXIVc), and XXVd). Treatment with acetic anhydride in the presence of sulphuric acid at room temperature gave the corresponding acetates (XXIIId) and (XXVId); at a higher temperature the unsaturated compound (XVd) was isolated.

Three methods were used for the preparation of nitroguaiacyl and nitrophenol ethers (XXXIa and XXXIb) containing sulphur in the chains, the most convenient being the condensation of the nitroguaiacyloxyalkyl or *p*-nitrophenoxyalkyl bromide (XXVIIa or XXVIIb) with sodium alkyl, arylalkyl, or aryl sulphide. In a second route, 5-(2-methoxy-4-nitrophenoxy)pentyl bromide (XXVIIa; $n = 5$) was converted successively into the thiouronium salt and the thiol (XXVIIIa), which was alkylated with methyl iodide. Another method is exemplified by the reaction of 1,3-dibromopropane with thiophenol to give 3-phenylthiopropyl bromide (XXIX) and subsequent condensation with potassium nitroguaiacyloxide. Corresponding sulphoxides (XXXIIb) and sulphones (XXXIVa

[14] Eglinton, Jones, and Whiting, *J.*, 1952, 2873.

XUM

and b) were obtained by oxidation with hydrogen peroxide in acetic acid, and one sulphone was prepared by condensation of the nitroguaiacyloxypentyl bromide (XXVIIa; $n = 5$) with *p*-acetamidobenzenesulphinic acid (XXXIII). The nitro-sulphones were reduced

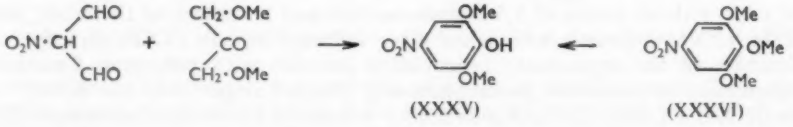


R = (a) O·C$_6$H$_3$(OMe)·NO$_2$-3,4, (b) O·C$_6$H$_4$·NO$_2$-*p*, (c) O·C$_6$H$_3$(OMe)·NH$_2$-3,4, (d) O·C$_6$H$_4$·NH$_2$-*p*.

to the amines (XXXIVc and d) catalytically, but chemical reduction was necessary for the amino-sulphides (XXXIc and d) and amino-sulphoxides (XXXIId). The diamine (XXXc) was formed when 5-(2-methoxy-4-nitrophenoxy)pentyl bromide (XXVIIa; $n = 5$) was heated with sodium sulphide.

Condensation of potassium 2-methoxy-4-nitrophenoxide with acetobromoglucose, followed by hydrolysis of the acetyl groups and reduction, afforded 4-amino-2-methoxyphenyl D-glucoside, presumably the β-isomer.[15]

To examine the effect of introducing a further methoxy-group at $C_{(6)}$ in the aminoguaiacyl ethers, 2,6-dimethoxy-4-nitrophenol (XXXV) was required. It seemed likely that the 2-methoxy-group of the known 5-nitropyrogallol trimethyl ether[16] (XXXVI)



would be sensitive to nucleophilic reagents and it was in fact preferentially attacked by aqueous alkali. The structure of the nitrophenol (XXXV) thus formed was confirmed by its independent synthesis from sodium nitromalondialdehyde and 1,3-dimethoxyacetone.[17] Condensations using this sterically hindered phenol were sluggish and required extended reaction times.

The *N*-substituted amines were for the most part obtained by standard methods, which have been described in earlier papers.[1,2]

Experimental

Light petroleum refers, except where stated, to the fraction of b. p. 40—60°.

Alcohols, bromides, and related compounds.

1-*Phenylbut*-3-*yl Bromide*.—Benzylideneacetone was reduced catalytically (Raney nickel) in ethanol to 4-phenylbutan-2-ol (92%), b. p. 119—121°/11 mm. (lit.,[18] 127°/18 mm.), which

[15] Koenigs and Knorr, *Ber.*, 1901, **34**, 957.
[16] Will, *Ber.*, 1888, **21**, 602.
[17] Jones and Kenner, *J.*, 1931, 1842.
[18] Jadot and Braine, *Bull. Soc. roy. Sci. Liége*, 1956, **25**, 62.

was refluxed for 20 hr. with 50% aqueous hydrobromic acid, giving the bromide (75% overall), b. p. 116°/10 mm. (lit.,[19] 116—118°/14 mm.). 4-Phenylbutyl bromide was prepared by the method of Oae and VanderWerf.[20]

Harper–Crombie Method for the Preparation of Phenylalkyl Bromides.—(*a*) A Grignard reagent prepared from benzyl chloride (189·75 g., 1·5 moles) and magnesium (36·45 g., 1·5 g.-atoms) in ether (400 ml.) was cooled and stirred whilst a solution of 2,3-dichlorotetrahydropyran (from 86 g. of dihydropyran *) in ether (200 ml.) was added during 1 hr. The mixture was stirred for a further 5 hr., kept overnight, and decomposed with ammonium chloride solution until the magnesium hydroxide separated as an easily filtrable solid. The suspension was filtered through Hyflo Supercel, the solid was washed with ether, and the ethereal solutions were washed, dried, and distilled, giving a mixture (145·4 g., 67%), b. p. 148—178°/15 mm. (Found: Cl, 14·4. Calc. for $C_{12}H_{15}ClO$: Cl, 16·9%), containing both *cis*- and *trans*-2-benzyl-3-chlorotetrahydropyran. Similar reactions were carried out with bromobenzene,[13] phenethyl bromide,[19] 3-phenylpropyl bromide, *o*-bromotoluene, *p*-bromotoluene, and *p*-bromoanisole, but in these cases the ethereal solutions were treated directly as in (*b*).

(*b*) 2-Benzyl-3-chlorotetrahydropyran (144 g. of crude mixture) was slowly added to a stirred (Hershberg wire stirrer) suspension of finely divided sodium (34·8 g.) in dry ether (500 ml.). Next day, the mixture was treated with ethanol (50 ml.), then water, and the washed and dried ethereal solution was distilled, giving the crude alcohol (107·7 g., 89·5%), b. p. 156—166°/12 mm. A redistilled sample of trans-6-*phenylhex*-4-*en*-1-*ol* had b. p. 152—157°/10 mm., n_D^{12} 1·5380 (Found: C, 81·5; H, 8·9. $C_{12}H_{16}O$ requires C, 81·8; H, 9·2%).

Similarly prepared (yields are for crude alcohol overall from dihydropyran) were *trans*-5-phenylpent-4-en-1-ol (77%), b. p. 102°/0·1 mm., 165—170°/21 mm., n_D^{20} 1·5620 (lit.,[11] b. p. 153—157°/13 mm., n_D^{17} 1·5640); *trans*-7-phenylhept-4-en-1-ol (51%), b. p. 100—105°/0·03 mm., n_D 1·5260 (lit.,[19] b. p. 110—118°/0·7 mm.); trans-8-*phenyloct*-4-*en*-1-*ol* (81%), b. p. 190—194°/15 mm., n_D^{19} 1·5240 (Found: C, 82·5; H, 9·7. $C_{14}H_{20}O$ requires C, 82·3; H, 9·9%); trans-5-o-*tolylpent*-4-*en*-1-*ol* (49%), b. p. 162—170°/15 mm., n_D 1·5505 (Found: C, 81·7; H, 9·25. $C_{12}H_{16}O$ requires C, 81·8; H, 9·1%); trans-5-p-*tolylpent*-4-*en*-1-*ol* (78%), m. p. 40—42°, b. p. 155—173°/14 mm. (Found: C, 82·3; H, 8·9%); and trans-5-p-*methoxyphenylpent*-4-*en*-1-*ol* (71%), m. p. 74—75° (Found: C, 75·1; H, 8·4. $C_{12}H_{16}O_2$ requires C, 75·0; H, 8·3%).

(*c*) Catalytic reduction of the unsaturated alcohols (Raney nickel) gave respectively 5-phenylpentanol (87%), b. p. 133—144°/11 mm., 6-phenylhexanol (93%), b. p. 157—167°/13 mm. (lit.,[21] b. p. 160—161°/13 mm.); 7-phenylheptanol (65%), b. p. 125—135°/0·02 mm., n_D 1·5135 (lit.,[21] b. p. 142—145°/7 mm.); 8-*phenyloctanol* (81%), b. p. 185—189°/12 mm., n_D^{19} 1·5080 (Found: C, 81·9; H, 10·5. $C_{14}H_{22}O$ requires C, 81·5; H, 10·75%); 5-o-*tolylpentanol* (86%), b. p. 155—156°/13 mm., n_D 1·5225 (Found: C, 80·9; H, 9·6. $C_{12}H_{18}O$ requires C, 81·0; H, 10·1%); 5-*p*-tolylpentanol (95%), b. p. 159—162°/14 mm. (lit.,[22] b. p. 158—159°/11 mm.); and 5-p-*methoxyphenylpentanol* (94%), b. p. 110—115°/0·03 mm. (Found: C, 74·5; H, 9·25. $C_{12}H_{18}O_2$ requires C, 74·2; H, 9·3%).

(*d*) The saturated alcohols were converted into the bromides by treatment with 50% aqueous hydrobromic acid (2 ml./g.) and concentrated sulphuric acid (0·67 ml./g.) at 100° for 20 hr. The following were obtained: 5-phenylpentyl bromide, 6-phenylhexyl bromide (used without purification);[20] 7-phenylheptyl bromide, b. p. 110—114°/0·05 mm. (lit.,[21] b. p. 170—175°/15 mm.); 8-*phenyloctyl bromide* (72%), b. p. 185—187°/12 mm. (Found: Br, 27·1. $C_{14}H_{21}Br$ requires Br, 29·7%); 5-o-*tolylpentyl bromide* (84%), b. p. 155—162°/14 mm. (Found: C, 59·45; H, 7·2; Br, 33·3. $C_{12}H_{17}Br$ requires C, 59·7; H, 7·1; Br, 33·2%); 5-p-*tolylpentyl bromide* (84%), b. p. 157—163°/14 mm. (Found: Br, 29·95. $C_{12}H_{17}Br$ requires Br, 33·2%).

5-*Phenylpent*-4-*en*-1-*yl toluene*-p-*sulphonate*, prepared (38%) in the usual way and crystallised from methanol at −80°, had m. p. 42—43° (Found: S, 10·5. $C_{18}H_{20}O_3S$ requires S, 10·1%). The toluene-*p*-sulphonates of 5-*p*-methoxyphenylpent-4-en-1-ol, 5-*p*-tolylpent-4-en-1-ol, and

* On several occasions, when the passage of chlorine through the ethereal solution of dihydropyran was interrupted so that the increase in weight could be measured, a bright flash travelled up the delivery tube leaving a carbonaceous deposit. This occurred with several batches of dihydropyran, all of which had been freshly distilled from sodium, and usually when the uptake was nearly complete.

[19] Bateman, Cunneen, and Lyons, *J.*, 1951, 2290.
[20] Oae and VanderWerf, *J. Amer. Chem. Soc.*, 1953, **75**, 5037.
[21] von Braun, *Ber.*, 1911, **44**, 2867.
[22] von Braun and Kühn, *Ber.*, 1927, **60**, 2557.

XUM

5-*p*-methoxyphenylpentanol were similarly prepared, but used without purification. When the toluene-*p*-sulphonate of 5-*p*-tolylpent-4-en-1-ol was prepared in pyridine, but the mixture was left for several days before being worked up, the product was the quaternary *pyridinium salt*, m. p. 68—69° (Found: C, 68·95; H, 6·75; N, 3·4; S, 7·8%; *M*, 409. $C_{24}H_{27}NO_3S,0{\cdot}5H_2O$ requires C, 68·9; H, 6·7; N, 3·3; S, 7·8%; *M*, 418).

5-Phenylpent-4-en-1-yl bromide was obtained from tetrahydro-2-phenylpyran as described by Paul.[23] 1-Methyl-5-phenylpentyl bromide, prepared by catalytic reduction of cinnamylideneacetone [24] and subsequent treatment with 50% aqueous hydrobromic acid, had b. p. 152—156°/14 mm., n_D^{20} 1·5218 (lit.,[25] b. p. 152—156°/10 mm.).

5-Cyclohexylpentan-1-ol was prepared (90%) by reduction of 5-phenylpent-4-en-1-ol over Raney nickel in ethanol at 131°/100 atm. It had b. p. 136—137°/11 mm., n_D^{17} 1·4685 (lit.,[26] b. p. 118—119°/4 mm., n_D^{25} 1·4638). Treatment with hydrobromic–sulphuric acid as described above gave 5-cyclohexylpentyl bromide (91%), b. p. 127°/7 mm., n_D^{20} 1·4838 (lit.,[26] b. p. 113—114°/5 mm., n_D^{25} 1·4814).

3,4-*Dihydro*-6-*phenyl*-2H-*pyran*.—Sodamide (15·6 g.) was ground in a ball-mill under toluene (50 ml.) for 30 hr. and to the resulting cream, stirred and refluxed in toluene (50 ml.), was added during 30 min. a solution of 3-chlorotetrahydro-2-phenylpyran (19·65 g.) in toluene (50 ml.). After a further 17 hr. the cooled mixture was treated with water, and the washed and dried toluene solution was distilled, giving the dihydrophenylpyran (78%), b. p. 119—125°/9 mm., n_D^{17} 1·5703 (lit.,[12] b. p. 125°/11 mm., n_D^{17} 1·5720). When heated with 50% aqueous hydrobromic acid for 15 min. at 100°, it yielded 4-benzoylbutyl bromide (94%), m. p. 58° (lit.,[12] m. p. 61°).

Ethyl α-(4-p-*Methoxyphenoxybutyl*)*benzoylacetate*.—4-*p*-Methoxyphenoxybutyl bromide (67·5 g.), dissolved in ethanol (50 ml.), and benzoylacetic ester (50 g.) were added successively to a solution of sodium (6·1 g.) in ethanol (150 ml.). The mixture was refluxed for 3 hr., then concentrated, diluted with water, and extracted with ether. The residue crystallised on trituration with light petroleum. Recrystallisation of the crude product (62 g., 64%) from ethanol afforded the pure *ester* (50 g.), m. p. 38—40° (Found: C, 71·6; H, 7·05. $C_{22}H_{26}O_5$ requires C, 71·3; H, 7·0%).

1-*Benzoyl*-5-p-*methoxyphenoxypentane*.—A mixture of the foregoing ester (50 g.), potassium hydroxide (20 g.), methanol (300 ml.), and water (200 ml.) was stirred and refluxed for 24 hr., then evaporated. The residue was extracted with ether and the washed and dried ethereal solution was evaporated. Trituration of the residue with light petroleum gave the *ketone* (34·3 g., 88%) (Found: C, 76·3; H, 7·8. $C_{19}H_{22}O_3$ requires C, 76·5; H, 7·4%), m. p. 42° not raised by recrystallisation from light petroleum.

The alkaline mother-liquors on acidification gave 6-p-*methoxyphenoxyhexanoic acid* (1 g.), m. p. 80—82° (Found: C, 65·8; H, 7·6. $C_{13}H_{18}O_4$ requires C, 65·5; H, 7·6%), and benzoic acid.

5-*Benzoylpentyl Bromide*.—A mixture of 1-benzoyl-5-*p*-methoxyphenoxypentane (34·5 g.), phenol (30 g.), and 50% hydrobromic acid (100 ml.) was stirred and refluxed for 2 hr., then cooled, and cautiously added to aqueous sodium hydroxide and ice. The product was extracted with ether and the washed and dried solution was distilled, giving the *bromide* (17·3 g., 59%), b. p. 190—200°/14 mm., m. p. 33—34°. After recrystallisation from light petroleum (b. p. 60—80°), it had m. p. 37·5—38·5° (Found: Br, 30·6. $C_{13}H_{15}BrO$ requires Br, 31·4%).

6-*Benzoylhexyl Bromide*.—1,5-Dibromopentane (46 g.) and benzoylacetic ester (19·2 g.) were added successively to a solution of sodium (2·3 g.) in dry ethanol (70 ml.), and the mixture was refluxed for 1·5 hr., concentrated, diluted with water, and extracted with ether. The extract was evaporated and the residue was stirred with 50% hydrobromic acid (100 ml.) on the steam-bath for 18 hr. The mixture was then diluted and extracted with ether and the washed and dried extract was distilled, giving 6-*benzoylhexyl bromide* (14·7 g., 55%), b. p. 140—150°/0·03 mm. (Found: Br, 27·75. $C_{13}H_{17}BrO$ requires Br, 29·7%).

5-(2-*Methoxy*-4-*nitrophenoxy*)*pentyl Bromide*.—A mixture of potassium 2-methoxy-4-nitrophenoxide (220·5 g., 93·9% pure), 1,5-dibromopentane (1150 g.), and acetone (3 l.) was refluxed for 20 hr., concentrated to low bulk and steam-distilled. The residue was extracted thrice with chloroform and the combined extracts were washed with 2N-sodium hydroxide and water,

[23] Paul, *Bull. Soc. chim. France*, 1935, **2**, 311.
[24] Roblin, Davidson, and Bogert, *J. Amer. Chem. Soc.*, 1935, **57**, 151.
[25] von Braun, Deutsch, and Schmatloch, *Ber.*, 1912, **45**, 1246.
[26] Hiers and Adams, *J. Amer Chem. Soc.*, 1926, **48**, 2388.

concentrated, and diluted with an equal volume of methanol. The crude bromide (252 g.; m. p. 75—76°) was purified by dissolving it in ether and filtering it from 1,5-di-(2-methoxy-4-nitrophenoxy)pentane (8·85 g., m. p. 122—123°). Concentration of the ethereal solution gave the *bromide* (218 g.), m. p. 76—77° (Found: Br, 23·8. $C_{13}H_{16}BrNO_4$ requires Br, 25·1%). 3-(2-*Methoxy*-4-*nitrophenoxy*)*propyl bromide*, m. p. 77·5—79° (from methanol) (Found: N, 4·9; Br, 27·5. $C_{10}H_{12}BrNO_4$ requires N, 4·8; Br, 27·5%), was similarly prepared.

Nitro- and acylamino-compounds.

7-(2-*Methoxy*-4-*nitrophenoxy*)-1-*phenylhepyl Acetate*.—7-(2-Methoxy-4-nitrophenoxy)-1-phenylheptan-1-ol (Table 1) (39 g.) was mixed with acetic anhydride (150 ml.) and treated with one drop of concentrated sulphuric acid. Ice was added after the mixture had been kept for 15 min. at room temperature. When the acetic anhydride had been decomposed the product was extracted with ether, and the extract washed with water, dried, and evaporated. The oil solidified under light petroleum containing a small quantity of ether. The solid was collected and recrystallised from methanol, to give the pure *acetate* (37 g., 89·5%), m. p. 88—89° (Found: C, 65·85; H, 6·8; N, 3·45. $C_{23}H_{27}NO_6$ requires C, 65·8; H, 6·8; N, 3·5%). In an earlier experiment the mixture was refluxed for 1 hr., and the product was recrystallised from ether, yielding 7-(2-*methoxy*-4-*nitrophenoxy*)-1-*phenylhept*-1-*ene* (7·0 g., 35%), m. p. 97—99° (Found: C, 70·05; H, 6·4; N, 4·0. $C_{20}H_{23}NO_4$ requires C, 70·35; H, 6·8; N, 4·1%). Its structure was confirmed by catalytic reduction to the known 1-(4-amino-2-methoxyphenoxy)-7-phenylheptane (Table 2).

Similarly prepared was 5-(2-*methoxy*-4-*nitrophenoxy*)-1-*phenylpentyl acetate* (71%), m. p. 114—115° (Found: C, 64·55; H, 6·35; N, 3·7. $C_{20}H_{23}NO_6$ requires C, 64·3; H, 6·2; N, 3·7%).

5-(2-*Methoxy*-4-*nitrophenoxy*-1-*phenylpentan*-1-*one Diethyl Acetal*.—1-Benzoyl-4-(2-methoxy-4-nitrophenoxy)butane (15 g.) in ethanol (100 ml.) was treated with ethyl orthoformate (5·8 g.) and one drop of concentrated hydrochloric acid. After 3 days at about 35—40° the mixture was filtered from some starting material (4·8 g.) and concentrated. Ether was added and a further quantity of starting material (1·2 g.) was collected. The ether was removed from the filtrate, and the product was recrystallised from ether–light petroleum, to give the *diethyl acetal* (10·2 g., 55·5%), m. p. 62—64° (Found: C, 65·5; H, 7·4; N, 3·55. $C_{22}H_{29}NO_6$ requires C, 65·5; H, 7·2; N, 3·5%).

Ethyl α-(4-p-*nitrophenoxybutyl*)*benzoylacetate* was prepared (62%) from benzoylacetic ester and 4-*p*-nitrophenoxybutyl bromide as described above for the *p*-methoxy-derivative. After crystallisation from methanol it had m. p. 74—75° (Found: C, 65·1; H, 5·9; N, 3·8. $C_{21}H_{23}NO_6$ requires C, 65·5; H, 6·0; N, 3·6%).

6-p-*Nitrophenoxy*-1-*phenylhexan*-1-*one*.—(*a*) The foregoing ester (33·3 g.) was hydrolysed by potassium hydroxide (13 g.) in refluxing methanol (250 ml.) and water (250 ml.) for 24 hr. The *ketone* (80%), recrystallised from ethanol, had m. p. 102° (Found: C, 69·1; H, 6·0; N, 4·5. $C_{18}H_{19}NO_4$ requires C, 69·0; H, 6·1; N, 4·5%). 6-*p*-Nitrophenoxyhexanoic acid (1·8 g.), m. p. 103—104°, not depressed by an authentic sample,[2] was isolated from the alkaline mother-liquors. In an experiment which was similar except that less water was used, the product was largely the acid, with only a small amount of ketone.

(*b*) The same compound was obtained (76%) by condensation of potassium *p*-nitrophenoxide with 5-benzoylpentyl bromide.

5-p-*Nitrophenoxy*-1-*phenylpentan*-1-*one* was similarly obtained from benzoylacetic ester and 3-*p*-nitrophenoxypropyl bromide in 26% overall yield. 5-*p*-Nitrophenoxypentanoic acid (13%) was also formed. The ketone has been previously made from benzoylbutyl bromide.[1]

6-p-*Nitrophenoxy*-1-*phenylhexan*-1-*ol* was prepared (94%) by reduction (Meerwein–Ponndorf method [1]) of the corresponding nitro-ketone. After crystallisation from light petroleum (b. p. 100—120°) it had m. p. 72—74° (Found: C, 68·7; H, 6·75. $C_{18}H_{21}NO_4$ requires C, 68·5; H, 6·7%).

S-5-(2-*Methoxy*-4-*nitrophenoxy*)*pentylthiourea*.—A mixture of 5-(2-methoxy-4-nitrophenoxy)-pentyl bromide (63·6 g.), thiourea (15·2 g.), and ethanol (150 ml.) was refluxed for 20 hr., cooled, and diluted with an equal volume of ether. The *thiouronium bromide* (93%) had m. p. 158—159° (from ethanol) (Found: Br, 18·95; S, 7·9. $C_{13}H_{19}N_3O_4S,HBr$ requires Br, 20·3; S, 8·1%).

5-(2-*Methoxy*-4-*nitrophenoxy*)*pentane*-1-*thiol*.—A mixture of the foregoing thiouronium salt (95 g.) and 1·86N-sodium hydroxide (129 ml.) was refluxed for 3 hr. (under nitrogen), cooled, and extracted with chloroform. The dried extract on evaporation afforded the *thiol* (79%),

XUM

m. p. 77—80°. A distilled specimen, b. p. 216°/0·2 mm., was crystallised from ether and had m. p. 84—86° (Found: N, 5·2; S, 11·6%; *M*, 299. $C_{12}H_{17}NO_4S$ requires N, 5·2; S, 11·8%; *M*, 271). On several occasions, samples suddenly decomposed during distillation.

1-(2-*Methoxy*-4-*nitrophenoxy*)-5-*methylthiopentane*.—A mixture of the foregoing thiol (6·15 g.) and a solution from sodium (0·52 g.) in ethanol (30 ml.) was refluxed whilst methyl iodide (3·55 g., 1·1 mol.) in ethanol (10 ml.) was added during 15 min. After a further 4 hr. the mixture was evaporated and the residue was dissolved in chloroform. The washed and dried extract was distilled, giving the *sulphide* (55%), b. p. 185—205°/0·15 mm., m. p. 56—59°. A specimen recrystallised from ether had m. p. 59—61° (Found: C, 55·05; H, 6·85; S, 11·4. $C_{12}H_{19}NO_4S$ requires C, 54·7; H, 6·7; S, 11·2%).

1-2′-*Hydroxyethylthio*-5-(2-*methoxy*-4-*nitrophenoxy*)*pentane*.—2-Mercaptoethanol (15·6 g.) and 5-(2-methoxy-4-nitrophenoxy)pentyl bromide (60·4 g.) were added successively to a solution from sodium (4·6 g.) in ethanol (150 ml.), and the mixture was refluxed for 1 hr., cooled, and filtered. The filtrate was concentrated and diluted with ether. The crystalline product was washed with ether and water, and crystallised from methanol to give the *sulphide* (52%), m. p. 52—54° (Found: N, 4·5; S, 9·95. $C_{14}H_{21}NO_5S$ requires N, 4·4; S, 10·2%).

Similarly prepared were 1-*benzylthio*-3-(2-*methoxy*-4-*nitrophenoxy*)*propane* (80%), m. p. 51—53° (from methanol–ethanol) (Found: N, 4·2; S, 9·3. $C_{17}H_{19}NO_4S$ requires N, 4·2; S, 9·6%), 1-(2-*methoxy*-4-*nitrophenoxy*)-5-*phenylthiopentane* (83%), m. p. 54—55° (from ether–light petroleum) (Found: C, 62·6; H, 6·4; S, 9·35. $C_{18}H_{21}NO_4S$ requires C, 62·2; H, 6·1; S, 9·2%), and 1-p-*chlorophenylthio*-5-(2-*methoxy*-4-*nitrophenoxy*)*pentane* (76%), m. p. 67—69° (from ethanol–ether) (Found: N, 3·7; S, 8·0. $C_{18}H_{20}ClNO_4S$ requires N, 3·7; S, 8·4%).

Similarly prepared, but by using 5-*p*-nitrophenoxypentyl bromide, were 1-p-*nitrophenoxy*-5-*phenylthiopentane* (90%), m. p. 67° (from ethanol) (Found: N, 4·3; S, 10·5. $C_{17}H_{19}NO_3S$ requires N, 4·4; S, 10·1%), 1-p-*nitrophenoxy*-5-p-*nitrophenylthiopentane* (88%), m. p. 83—84° (from acetic acid) (Found: N, 7·7; S, 8·8. $C_{17}H_{18}N_2O_5S$ requires N, 7·7; S, 8·8%), and 5-*benzylthio*-1-p-*nitrophenoxypentane* (77%), m. p. 33—34° (from ethanol) (Found: N, 4·05; S, 9·7. $C_{18}H_{21}NO_3S$ requires N, 4·2; S, 9·7%).

1-(2-*Methoxy*-4-*nitrophenoxy*)-3-*phenylthiopropane*.—Thiophenol (11·0 g.) was added to a solution from sodium (2·3 g.) in dry ethanol (100 ml.), followed by 1,3-dibromopropane (40·4 ml.). After being refluxed for 0·5 hr. the mixture was concentrated and the residue dissolved in ether; the solution was washed with water, dried, and concentrated. Excess of 1,3-dibromopropane was removed by steam-distillation and the residual 3-phenylthiopropyl bromide was condensed with potassium 2-methoxy-4-nitrophenoxide to give the *nitro-compound* (54%), m. p. 87—89° (from ethanol) (Found: N, 4·5; S, 10·15. $C_{16}H_{17}NO_4S$ requires N, 4·4; S, 10·0%).

1-(2-*Methoxy*-4-*nitrophenoxy*)-5-*phenylsulphonylpentane*.—1-(2-Methoxy-4-nitrophenoxy)-5-phenylthiopentane (27 g.) in acetic acid (200 ml.) was treated with 30% w/v hydrogen peroxide (20 ml.); the temperature rose to 50°. After 2·5 hr. the solution was heated at 90° for 1 hr., cooled, and poured into water. The product slowly solidified and recrystallised from ethanol, to give the *sulphone* (88%), m. p. 122—124° (Found: C, 57·6; H, 5·9; S, 8·2. $C_{18}H_{21}NO_6S$ requires C, 57·0; H, 5·6; S, 8·4%).

Similarly prepared were: 1-(2-*methoxy*-4-*nitrophenoxy*)-5-*methylsulphonylpentane* (66%), m. p. 95—97% (from ethanol) (Found: N, 4·5; S, 9·7. $C_{13}H_{19}NO_6S$ requires N, 4·4; S, 10·1%); 1-p-*nitrophenoxy*-5-*phenylsulphonylpentane* (97%), m. p. 85—86° (from ethanol) (Found: C, 58·1; H, 5·8; N, 3·9. $C_{17}H_{19}NO_5S$ requires C, 58·5; H, 5·45; N, 4·0%); 1-p-*nitrophenoxy*-5-p-*nitrophenylsulphonylpentane* (94%), m. p. 129—130° (from acetic acid) (Found: N, 7·1; S, 8·1. $C_{17}H_{18}N_2O_7S$ requires N, 7·1; S, 8·1%); and 1-*benzylsulphonyl*-5-p-*nitrophenoxypentane* (88%), m. p. 120—121° (from acetic acid) (Found: C, 59·25; H, 6·1; N, 3·8. $C_{18}H_{21}NO_5S$ requires C, 59·5; H, 5·8; N, 3·9%).

1-p-*Acetamidophenylsulphonyl*-5-p-*nitrophenoxypentane*.—A mixture of 5-*p*-nitrophenoxypentyl bromide (28·8 g.), *p*-acetamidobenzenesulphinic acid (19·9 g.), sodium acetate (7·0 g.), sodium iodide (2·0 g.), 2-ethoxyethanol (200 ml.), and water (5 ml.) was refluxed for 2·5 hr., concentrated and diluted with water. Recrystallisation of the product from ethanol afforded the *sulphone* (55%), m. p. 112—113° (Found: C, 56·4; H, 5·5; N, 6·6. $C_{19}H_{22}N_2O_6S$ requires C, 56·2; H, 5·4; N, 6·9%).

5-p-*Nitrophenoxypentyl Phenyl Sulphoxide*.—30% Hydrogen peroxide (14·6 ml.) was added to a solution of 1-*p*-nitrophenoxy-5-phenylthiopentane (40 g.) in acetic acid (400 ml.) at 40°. The solution was heated at 80° for 30 min., cooled, diluted with water, and filtered. The

product was recrystallised from ethanol, giving the *sulphoxide* (98%), m. p. 80—81° (Found: C, 60·6; H, 5·7; N, 4·2. $C_{17}H_{19}NO_4S$ requires C, 61·3; H, 5·7; N, 4·2%). Similarly prepared was *benzyl* 5-p-*nitrophenoxypentyl sulphoxide* (92%), m. p. 97—98° (from aqueous ethanol) (Found: C, 62·0; H, 6·15; N, 4·05. $C_{18}H_{21}NO_4S$ requires C, 62·2; H, 6·05; N, 4·0%).

2-*Methoxy*-4-*nitrophenyl Tetra*-O-*acetyl*-D-*glucoside*.—A mixture of potassium 2-methoxy-4-nitrophenoxide (14·1 g., dried azeotropically with benzene), acetobromoglucose (28 g.), and dimethylformamide (100 ml.) was stirred for 20 hr., then filtered, and the solid was washed with benzene (200 ml.). The combined solutions were evaporated under reduced pressure, and the residue, in benzene, was stirred with activated alumina (7 × 20 g.) to remove free phenol. The filtered solution was evaporated and the residue crystallised from ether, to give the *glucoside* (49%), m. p. 145—147° (Found: C, 50·7; H, 5·2; N, 2·9. $C_{21}H_{25}NO_{13}$ requires C, 50·5; H, 5·05; N, 2·8%). The same compound was obtained in traces on using the free phenol, silver carbonate, quinoline, and acetobromoglucose in ether.

2-*Methoxy*-4-*nitrophenyl* D-*Glucoside*.—The foregoing tetra-acetate (33·2 g.) in methanol (340 ml.) was treated with a solution of sodium hydroxide (11·2 g.) in a small amount of water and methanol (170 ml.) and kept for 30 min. The *product*, which separated, was filtered off and crystallised from methanol; it then had m. p. 212—213° (Found: C, 47·3; H, 4·9; N, 4·4. $C_{13}H_{17}NO_9$ requires C, 47·1; H, 5·2; N, 4·2%).

4-*Acetamido*-2-*methoxyphenol*.—2-Methoxy-4-nitrophenol (31 g.) was reduced over platinum oxide in ethanol (300 ml.). The resulting suspension (still containing catalyst) was evaporated under reduced pressure and the residue was refluxed for 30 min. with acetic anhydride (50 ml.), cooled, and filtered. The solid was washed with ether and crystallised from ethanol, giving the diacetyl derivative (50%), m. p. 150—152° (lit.,[27] 147°).

4-Acetamido-2-methoxyphenyl acetate (54 g.) was shaken with 2N-aqueous sodium hydroxide (242 ml.) containing wetting agent (" Lissapol," 1 drop) until dissolved (10 min.). The solution was filtered (charcoal), cooled in ice, and acidified with concentrated hydrochloric acid (53 ml.). The precipitated 4-acetamido-2-methoxyphenol (98%, m. p. 114—116°), after recrystallisation from ethyl acetate, had m. p. 115—117° (lit.,[8] m. p. 118°).

1-(4-*Acetamido*-2-*methoxyphenoxy*)-5-p-*nitrophenylpentane*.—4-Acetamido-2-methoxyphenol (15·35 g.) and 5-*p*-nitrophenylpentyl bromide [2] (23·1 g. of the crude product from the nitration of 5-phenylpentyl bromide) were added to a solution from sodium (1·95 g.) in ethanol (100 ml.), and the mixture was stirred and refluxed for 20 hr., then evaporated under reduced pressure. The residue was shaken with chloroform and water, and the chloroform solution was separated, dried, concentrated, and treated with ethyl acetate. The *product*, which separated, was recrystallised from methanol (yield 21%), and then had m. p. 115·5—116° (Found: C, 64·65; H, 6·7; N, 7·3. $C_{20}H_{24}N_2O_5$ requires C, 64·5; H, 6·5; N, 7·2%).

1-(2-*Hydroxy*-4-*nitrophenoxy*)-5-*phthalimidopentane*.—4-Nitrocatechol (18·2 g.) and 5-phthalimidopentyl bromide (34·7 g.) were added to 2-ethoxyethanol (100 ml.) and a solution of potassium hydroxide (6·6 g.) in water (20 ml.). The mixture was refluxed for 20 hr., cooled, and diluted with water. Recrystallisation of the product from acetic acid gave the *phthalimide* (41%), m. p. 137—139° (Found: N, 7·7. $C_{19}H_{18}N_2O_6$ requires N, 7·6%).

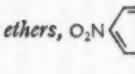
1-(2-*Methoxy*-4-*nitrophenoxy*)-5-*phthalimidopentane*.—A mixture of the foregoing hydroxy-compound (0·77 g.), anhydrous potassium carbonate (0·3 g.), methyl iodide (4 ml.), and acetone (30 ml.) was refluxed for 20 hr., then evaporated. The residue was treated with aqueous ethanol and the insoluble solid was crystallised from acetic acid. It had m. p. 147·5—148·5°, not depressed by a specimen prepared directly from 2-methoxy-4-nitrophenol (see Table 1).

1-(2-*Methoxy*-5-*nitrophenoxy*)-5-*phenylpentane*, m. p. 73—75° (from ethanol) (Found: C, 68·9; H, 6·9; N, 4·4. $C_{18}H_{21}NO_4$ requires C, 68·5; H, 6·7; N, 4·4%), was prepared (81%) from 2-methoxy-5-nitrophenol,[28] 5-phenylpentyl bromide, and 10N-aqueous potassium hydroxide in 2-ethoxyethanol.

1,2,3-*Trimethoxy*-5-*nitrobenzene*.—Nitric acid (*d* 1·42; 20 ml.) was added fairly slowly to 1,2,3-trimethoxybenzene (30 g.) in acetic acid (60 ml.). When the temperature reached 90—100°, ice-water was added. The product was washed well with water, and (by stirring) with hot dilute sodium hydroxide. It was re-washed with water, and crystallised from ethanol; it then had m. p. 100—102° (lit.,[11] m. p. 100°). The yield (39—41%) was reduced when more dilute nitric acid was employed.

[27] Kehrmann and Hoehn, *Helv. Chim. Acta*, 1925, **8**, 218.
[28] Paul, *Ber.*, 1906, **39**, 2773; Reverdin and Crépieux, *Ber.*, 1906, **39**, 4232.

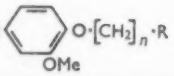
XUM

TABLE 1. *Nitroguaiacyl ethers,* O_2N  $O\cdot[CH_2]_n\cdot R$

						Found (%)			Required (%)		
n	R	Yield (%)	M. p.	Solvent[a]	Formula	C	H	N	C	H	N
4	Me	71	54—55°	EtOH	$C_{12}H_{17}NO_6$	60·4	7·55	5·9	60·4	7·2	5·85
5	Me	69	69·5—70·5	EtOH	$C_{13}H_{19}NO_6$	62·1	7·7	5·45	61·7	7·5	5·5
6	Me	63	53—55	EtOH	$C_{14}H_{21}NO_6$	63·1	8·0	5·0	62·9	7·9	5·3
7	Me	87	37—38	EtOH–H_2O	$C_{15}H_{23}NO_6$	64·2	8·4	5·0	64·0	8·2	5·0
8	Me		[b]		$C_{16}H_{25}NO_6$						
9	Me	73	50	EtOH	$C_{17}H_{27}NO_6$	65·8	8·8	4·05	66·0	8·8	4·5
10	Me	87	49·5—50·5	EtOH	$C_{18}H_{29}NO_6$	66·9	9·2	4·45	66·9	9·0	4·3
11	Me	73	51—52·5	EtOH	$C_{19}H_{31}NO_6$	67·3	9·5	4·3	67·6	9·2	4·2
15	Me	73	57—58·5	EtOH	$C_{23}H_{39}NO_6$	70·55	10·35	3·5	70·2	9·9	3·6
1	$CHEt_2$	45	[c]		$C_{15}H_{21}NO_6$	61·6	7·3	5·7	61·65	7·6	5·5
1	$CHEtBu^n$	44	[d]		$C_{16}H_{23}NO_6$			5·1			5·0
0	$CHMe\cdot C_8H_{17}$-n	18	42—43	MeOH	$C_{18}H_{25}NO_6$	64·2	8·2	5·0	64·0	8·25	5·0
1	$CHMe\cdot CH_2Bu^t$		[b]		$C_{16}H_{25}NO_6$						
0	$CHMe\cdot C_7H_{15}$-n	19[e]	[f]		$C_{16}H_{23}NO_6$	65·3	8·7	4·7	65·1	8·5	4·7
2	$CHMe\cdot[CH_2]_2\cdot CH_2Pr^i$	29	[g]		$C_{17}H_{27}NO_6$	66·1	8·9	4·6	66·0	8·8	4·5
0	Cyclopentyl	53	83—85	EtOH	$C_{13}H_{17}NO_6$	60·6	6·4	5·8	60·7	6·3	5·9
2	Cyclohexyl	64	78—80	EtOH	$C_{15}H_{21}NO_6$	64·2	7·6	5·1	64·5	7·6	5·0
5	Cyclohexyl	66	57—58	Pet	$C_{19}H_{29}NO_6$	67·5	8·2	4·3	67·3	8·5	4·35
1	$CH{:}CH_2$	85	51—52·5	Et_2O–Pet	$C_{12}H_{11}NO_6$	57·7	5·4	6·6	57·4	5·3	6·7
3	$CH{:}CH_2$	68[h]	65—66	EtOH–H_2O	$C_{14}H_{15}NO_6$	60·8	6·3	5·9	60·7	6·3	5·9
2	$CH{:}CHBu^n$	36[i]	[j]		$C_{16}H_{19}NO_6$	63·8	7·5	5·3	63·4	7·2	5·3
1	COMe	63	116—118	EtOH	$C_{10}H_{11}NO_6$	53·8	4·9	6·2	53·3	4·9	6·2
5	OAc	89[k]	75—76	EtOH	$C_{14}H_{19}NO_8$	56·9	6·65	4·8	56·6	6·4	4·7
1	CO_2Et	79[k]	86—88	MeOH	$C_{11}H_{13}NO_8$	52·0	5·35	5·6	51·8	5·1	5·5
1	CO_2H	91[m]	165·5—167	AcOH–H_2O	$C_9H_9NO_8$	47·1	4·0	6·1	47·6	4·0	6·2
2	NEt_2	49[n]	[o]		$C_{12}H_{20}N_2O_4$	58·35	7·5	10·2	58·2	7·5	10·4
1	Ph	70	80—82	$OH\cdot[CH_2]_2\cdot OEt$	$C_{14}H_{13}NO_6$	65·0	5·2	5·4	64·9	5·0	5·4
2	Ph	66	97—99	EtOH	$C_{15}H_{15}NO_6$	65·9	5·55	5·3	65·9	5·5	5·1
	Ph	85	72·5—73·5	EtOH	$C_{16}H_{17}NO_6$	67·25	5·75	4·9	66·9	5·9	4·9
4	Ph		[p]		$C_{17}H_{19}NO_6$						
0	$CHMe\cdot[CH_2]_3\cdot Ph$	55	50—51	EtOH	$C_{17}H_{19}NO_6$	67·7	6·4	4·5	67·75	6·4	4·65
5	Ph	81[q]	75—76[e]	EtOH	$C_{18}H_{21}NO_6$			4·4			4·4
6	Ph		55—57	Pet	$C_{19}H_{23}NO_6$	69·0	6·9	4·3	69·3	7·0	4·3
0	$CHMe\cdot[CH_2]_4\cdot Ph$	58	65·5—67·5	Et_2O–Pet	$C_{19}H_{23}NO_6$	69·45	7·15	4·3	69·3	7·0	4·3
7	Ph	59	73—74	EtOH	$C_{20}H_{25}NO_6$	69·7	7·4	4·2	69·9	7·3	4·1
8	Ph	62	49—50	$COMe_2$–EtOH	$C_{21}H_{27}NO_6$	70·4	7·6	3·95	70·6	7·6	3·9
5	C_6H_4Me-*o*	82	76—77	EtOH	$C_{19}H_{23}NO_6$	69·4	7·35	4·3	69·3	7·0	4·25
5	C_6H_4Me-*p*	84	76—78	EtOH	$C_{19}H_{23}NO_6$	69·2	7·2	4·3	69·3	7·0	4·25

5	C_6H_4·OMe-*p*	57[r]	81—82	EtOH	$C_{19}H_{23}NO_5$	66·2	6·9	4·1	66·1	6·7	4·1
5	C_6H_4·NO_2-*p*	45	84 and 93—94	$COMe_2$–EtOH	$C_{18}H_{20}N_2O_6$	60·1	5·8	7·95	60·0	5·6	7·8
5	$C_6H_3(NO_2)_2$-2,4	58	86—87	EtOAc	$C_{18}H_{19}N_3O_8$	53·1	4·6	10·4	53·3	4·7	10·4
3	·CH:CHPh-*trans*	74	95—97	EtOH	$C_{18}H_{19}NO_4$	69·0	5·9	4·5	69·0	6·1	4·5
3	·CH:CH·C_6H_4Me-*p*-*trans*	57	103—103·5	EtOAc–Pet[s]	$C_{19}H_{21}NO_4$	70·0	6·5	4·3	69·7	6·5	4·3
3	·CH:CH·C_6H_4·OMe-*p*-*trans*	60[t]	121—121·5	EtOH–EtOAc	$C_{19}H_{21}NO_5$	66·9	6·3	4·2	66·5	6·1	4·1
1	*p*-C_6H_4·SO_2Me	87	195—197	EtOH	$C_{18}H_{19}NO_6S$[u]			4·2			4·15
1	1-Naphthyl	62	110—111	EtOH–$COMe_2$	$C_{18}H_{17}NO_4$	69·7	5·15	4·7	69·9	4·9	4·5
1	OMe	82[v]	89—92	EtOH–Pet[w]	$C_9H_{11}NO_4$	50·6	5·35	6·5	50·7	5·2	6·6
5	OMe	66	[x]		$C_{13}H_{19}NO_6$			5·3			5·2
2	O·CH_2Ph	80[y]	75—77	EtOH	$C_{16}H_{17}NO_5$	63·3	5·8	4·7	63·4	5·6	4·6
5	O·CH_2Ph	71[z]	90—91	EtOH	$C_{21}H_{23}NO_5$	66·2	7·0	4·15	66·0	6·7	4·05
2	OPh	90	116—117	EtOH	$C_{15}H_{15}NO_5$	62·45	5·3	4·8	62·3	5·2	4·8
3	OPh	73	100—102	EtOH	$C_{16}H_{17}NO_5$	63·8	5·5	4·7	63·4	5·6	4·6
4	OPh	89	90—91·5	EtOH	$C_{17}H_{19}NO_5$	64·5	6·3	4·4	64·3	6·0	4·4
5	OPh	80	67—68	EtOH	$C_{18}H_{21}NO_5$	65·3	6·5	4·2	65·3	6·4	4·2
6	OPh	84	81—82	EtOH	$C_{19}H_{23}NO_5$	66·2	6·7	4·0	66·2	6·7	4·1
7	OPh	70	56—57	EtOH	$C_{20}H_{25}NO_5$	66·7	7·1	4·1	66·9	7·0	3·9
8	OPh	82	58—59	EtOH	$C_{21}H_{27}NO_5$	67·65	7·1	3·8	67·6	7·2	3·8
3	O·C_6H_4·OMe-*p*	32	96—97	EtOH	$C_{17}H_{19}NO_6$	61·6	5·6	4·2	61·2	5·8	4·2
4	O·C_6H_4·OMe-*p*	85	106—107	EtOH	$C_{18}H_{21}NO_6$	62·3	6·1	4·1	62·6	6·1	4·0
5	O·C_6H_4·NHAc-*p*	86	122—123	EtOH	$C_{20}H_{24}N_2O_6$[aa]			7·3			7·2
5	O·C_6H_4·NO_2-*p*	78	95—96	AcOH	$C_{18}H_{18}N_2O_7$			7·6			7·45
5	Phthalimido	78[ab]	147·5—148·5	AcOH	$C_{20}H_{19}NO_6$			7·3			7·3
6	Phthalimido	61	81—83	EtOH	$C_{21}H_{23}NO_6$	63·3	5·9	7·25	63·3	5·5	7·0
8	Phthalimido	79	91—92	AcOH	$C_{23}H_{25}NO_6$			6·5			6·6
5	NH·COPh	64[ac]	131—132	EtOAc	$C_{19}H_{22}N_2O_5$			7·9			7·8
5	NH·CO·CH_2·NH·COPh	95[ad]	129—130	$COMe_2$	$C_{21}H_{24}N_2O_6$			10·4			10·1
5	NH·CO·$[CH_2]_3$·CO_2H	99[ae]	94—97	$COMe_2$–Pet	$C_{17}H_{24}N_2O_7$	55·5	6·7	7·6	55·4	6·5	7·6
5	Glutarimido	83[af]	138—140	EtOH	$C_{17}H_{22}N_2O_6$	58·6	6·2	8·0	58·3	6·3	8·0
1	COPh	84	122—123	OEt·$[CH_2]_3$·OH	$C_{18}H_{19}NO_5$	62·4	4·8	4·7	62·7	4·5	4·9
4	COPh	59	91	OEt·$[CH_2]_3$·OH	$C_{18}H_{19}NO_5$	65·7	5·8	4·2	65·7	5·8	4·3
6	COPh	81	82—84	EtOH	$C_{20}H_{23}NO_5$	67·1	6·4	3·9	67·25	6·45	3·9
4	CHPh·OH	94[ag]	76—77	Et_2O–Pet	$C_{18}H_{21}NO_5$	65·2	6·6	4·1	65·2	6·4	4·2
6	CHPh·OH	89[ag]	62—63	Et_2O–Pet	$C_{20}H_{23}NO_5$	67·1	7·0	3·9	66·8	7·0	3·9

[a] Solvent for crystn. Pet = light petroleum (b. p. 40—60°, except where stated). [b] Not obtained crystalline; reduced directly to amine. [c] B. p. 150—170°/0·05 mm. [d] B. p. 164—184°/0·02 mm. [e] Toluene-*p*-sulphonate of alcohol used. [f] B. p. 186—194°/0·8 mm. [g] B. p. 204—215°/0·3 mm. [h] Overall from pent-4-en-1-ol, *via* the toluene-*p*-sulphonate.[s] [i] Overall from hept-3-en-1-ol *via* the toluene-*p*-sulphonate. [j] B. p. 164—186°/0·1 mm. [k] From nitroguaiacyloxypentyl bromide and KOAc (cf. ref. 3). [l] $CH_2Br·CO_2Et$ in acetone used. [m] By hydrolysis of the ethyl ester with 0·8N-aqueous sodium hydroxide. [n] From $CH_2Cl·CH_2·NEt_2$ in acetone. [o] B. p. 175—200°/0·15 mm. [p] Not obtained crystalline; reduced directly to amine. [q] Overall from 5-phenylpentanol. [r] Overall from 5-*p*-methoxyphenylpentanol. [s] B. p. 60—80°. [t] Overall from 5-*p*-methoxyphenylpent-4-en-1-ol. [u] Found: S, 9·4. Required, S, 9·5%. [v] From $CH_2Cl·OMe$. [w] B. p. 60—80°. [x] B. p. 170°/0·1 mm. [y] Toluene-*p*-sulphonate used. [z] From 5-benzyloxypentyl bromide (B.P. 770,870). [aa] Found: OMe, 8·0. Required OMe, 8·0%. [ab] Also prepared by methylation of the 2-hydroxy-compound (see text). [ac] By benzoylation of 5-(2-methoxy-4-nitrophenoxy)pentylamine. [ad] From 5-(2-methoxy-4-nitrophenoxy)pentylamine and 2-phenyloxazolone (cf. ref. 1). [ae] From 5-(2-methoxy-4-nitrophenoxy)pentylamine and glutaric anhydride (cf. ref. 1). [af] By cyclisation of the glutaramic acid with acetyl chloride (cf. ref. 1). [ag] By reduction (Meerwein–Ponndorf) of the ketone (cf. ref. 1).

TABLE 2. *Aminoguaiacyl ethers*, H_2N  $O\cdot[CH_2]_n\cdot R$

							Found (%)					Required (%)				
n	R	Derivative	Yield (%)	M. p.	Solvent [a]	Formula	C	H	N	S	Hal	C	H	N	S	Hal
1	Me	Base	86	60—61° [b]	Et_2O–Pet	$C_9H_{13}NO_3$			8·2					8·4		
2	Me	Base	87	65—67	Et_2O–Pet	$C_{10}H_{15}NO_3$	66·6	8·4	7·8			66·3	8·3	7·7		
3	Me	Base	77	35—36	Pet	$C_{11}H_{17}NO_3$	67·6	8·6	7·2			67·7	8·8	7·2		
		$Me\cdot SO_3H$		173—175	EtOH	$C_{11}H_{17}NO_3,CH_4O_3S$			4·9	10·9				4·8	11·0	
4	Me	Base	92	43—44	Pet	$C_{12}H_{19}NO_3$	69·15	9·3	6·7			68·9	9·15	6·7		
		HCl		185—200	EtOH–Et_2O	$C_{12}H_{19}NO_3,HCl$			5·75		14·3			5·7		14·45
5	Me	Base	91	67—69	EtOH	$C_{13}H_{21}NO_3$	70·1	9·3	6·2		69·9	9·4	6·3			
		HCl		185—200	EtOH–Et_2O	$C_{13}H_{21}NO_3,HCl$			5·2		13·9			5·4		13·7
6	Me	Base	92	72—74	EtOH	$C_{14}H_{23}NO_3$	70·85	9·75	5·9			70·9	9·7	5·9		
7	Me	Base	76	63—64	EtOH	$C_{15}H_{25}NO_3$	72·0	10·0	5·55			71·7	10·0	5·6		
		$Me\cdot SO_3H$		120—125 and 200		$C_{15}H_{25}NO_3,CH_4O_3S$			3·6	9·4				4·0	9·2	
		Diptolate [c]		161—162	EtOAc	$C_{15}H_{25}NO_3,C_{28}H_{16}O_8$	65·7	6·8	2·3			65·9	6·8	2·2		
8	Me	Base	64 [d]	71—73	Et_2O–Pet	$C_{16}H_{27}NO_3$	72·4	10·3	5·1			72·5	10·2	5·3		
9	Me	Base	84	61—62	Pet	$C_{17}H_{29}NO_3$	72·9	10·5	4·8			73·1	10·5	5·0		
10	Me	Base	95	66—67	EtOH	$C_{18}H_{31}NO_3$	73·7	10·4	4·8			73·7	10·65	4·8		
11	Me	Base	90	65—66	EtOH	$C_{19}H_{33}NO_3$	74·3	11·0	4·7			74·3	10·7	4·6		
15	Me	Base	85	67—68	Et_2O–Pet	$C_{23}H_{41}NO_3$	76·2	11·35	3·9			76·0	11·3	3·9		
1	$CHEt_2$	HBr	69	214—217	EtOH–Et_2O	$C_{15}H_{25}NO_3,HBr$			4·4		26·0			4·6		26·2
1	$CHEtBu^n$	HBr	55	160—164	Et_2O–C_6H_6	$C_{16}H_{29}NO_3,HCl$			4·9		12·1			4·9		12·3
0	$CHMe\cdot C_6H_{13}$-n	Base	83	•		$C_{16}H_{25}NO_3$	71·7	10·3	5·8			71·7	10·0	5·6		
		HCl		160—180	EtOH–Et_2O	$C_{16}H_{25}NO_3,HCl$			5·0		12·2			4·9		12·3
2	$CHMe\cdot CH_2Bu^t$	Base	62 [d]	72—73·5	Et_2O–Pet	$C_{16}H_{27}NO_3$	72·8	10·4	5·35			72·5	10·2	5·3		
0	$CHMe\cdot C_7H_{15}$-n	Base	49	[f]		$C_{16}H_{27}NO_3$	72·3	10·9	5·35			72·5	10·2	5·3		
		HCl		164—168		$C_{16}H_{27}NO_3,HCl$			4·8		11·6			4·65		11·75
2	$CHMe\cdot[CH_2]_3\cdot CH_2Pr^i$	HCl	59	158—164	EtOH–Et_2O	$C_{17}H_{29}NO_3,HCl$			4·3		11·4			4·4		11·2
0	Cyclopentyl	Base	83	64—66	EtOH–Pet [g]	$C_{15}H_{17}NO_3$	69·8	8·4	6·8			69·6	8·2	6·8		
2	Cyclohexyl	Base	80	64—65	Pet [g]	$C_{15}H_{23}NO_3$	71·85	9·1	5·65			72·2	9·3	5·6		
5	Cyclohexyl	Base	80	91—91·5	MeOH	$C_{16}H_{25}NO_3$	74·6	9·8	4·85			74·3	10·0	4·8		
3	$CH{:}CH_2$	Base	90 [h]	25—26	Et_2O–Pet	$C_{13}H_{17}NO_3$	69·4	8·3	6·8			69·5	8·2	6·8		
		HBr		195—197	Dil. aq. HBr	$C_{13}H_{17}NO_3,HBr$			4·85		27·5			4·9		27·8
2	$CH{:}CHBu^n$	Base	42 [h]	38—42	Pet	$C_{14}H_{21}NO_3$	71·7	9·3	6·1			71·5	9·0	5·95		
1	$CHMe\cdot OH$	Base	78 [i]	125—126	EtOH	$C_{10}H_{15}NO_3$	60·7	7·6	7·0			60·9	7·7	7·1		
5	OAc	Base	71	46—48	EtOH–H_2O	$C_{14}H_{21}NO_4$	62·5	7·75	5·2			62·9	7·9	5·2		
5	OH	Base	93 [j]	70—71	$CHCl_3$–Pet	$C_{12}H_{19}NO_3$	63·9	8·6	6·15			64·0	8·45	6·2		
1	CO_2H	Base	93	200—202	H_2O	$C_9H_{11}NO_5$	54·4	5·6	7·2			54·8	5·6	7·1		
2	NEt_2	2HBr	81	216—218	MeOH–Et_2O	$C_{13}H_{22}N_2O_3,2HBr$			6·7		39·7			6·9		39·6
1	Ph	Base	39	84—85	Pet [k]	$C_{14}H_{15}NO_3$	73·1	6·5	5·95			73·4	6·6	6·1		
		$Me\cdot SO_3H$		200—201	EtOH–Et_2O	$C_{14}H_{15}NO_3,CH_4O_3S$			4·05	9·9				4·3	9·8	
2	Ph	Base	78	47—48	Et_2O–Pet	$C_{15}H_{17}NO_3$	73·75	6·85	5·8			74·1	7·0	5·8		
		$Me\cdot SO_3H$		159—160	EtOH–Et_2O	$C_{15}H_{17}NO_3,CH_4O_3S$			4·1	9·65				4·1	9·4	
3	Ph	Base	90	103—104	EtOH	$C_{16}H_{19}NO_3$	74·95	7·4	5·5			74·7	7·4	5·4		
		$Me\cdot SO_3H$		159—160	EtOH–Et_2O	$C_{16}H_{19}NO_3,CH_4O_3S$			4·1	9·05				4·0	9·1	
4	Ph	$Me\cdot SO_3H$	60	123—124	EtOH	$C_{17}H_{21}NO_3,CH_4O_3S$			3·7	8·8				3·8	8·7	

5	Ph	Base	90 [m]	77—78	EtOH	$C_{16}H_{23}NO_2$	76·05	8·4	4·8			75·75	8·1	4·9		
		$Me·SO_3H$	86 [n]	138·5—139·5		$C_{16}H_{23}NO_5S,CH_4O_3S$			3·6	8·5				3·7	8·4	
		HCl		147—149 (clears 158—160)	EtOH–Et_2O	$C_{16}H_{23}NO_2,HCl$			4·3		11·0			4·3		11·1
6	Ph	Base	38 [o]	39—41	Et_2O–Pet	$C_{17}H_{25}NO_2$	76·4	8·35	4·7			76·2	8·4	4·7		
0	$CHMe·[CH_2]_4·Ph$	Base	70	42—44	Et_2O–Pet	$C_{19}H_{29}NO_2$	76·1	8·4	4·7			76·2	8·4	4·7		
7	Ph	Base	80	65	EtOH–Pet	$C_{20}H_{31}NO_2$	76·75	8·9	4·3			76·6	8·7	4·5		
8	Ph	Base	87	52—53	Et_2O–Pet	$C_{21}H_{33}NO_2$	76·7	8·8	4·3			77·0	8·8	4·3		
5	C_6H_4Me-*o*	Base	73	69—71	EtOH–H_2O	$C_{19}H_{25}NO_2$	76·1	8·45	4·5			76·2	8·4	8·7		
5	C_6H_4Me-*p*	Base	91	84—86	EtOH–Pet	$C_{19}H_{25}NO_2$	76·35	8·6	4·7			76·2	8·4	4·7		
5	$C_6H_4·OMe$-*p*	Base	93	98—100	EtOH	$C_{19}H_{25}NO_3$	72·5	8·0	4·45			72·4	7·9	4·45		
5	$C_6H_4·NO_2$-*p*	Base	82 [p]	86—87	EtOH	$C_{18}H_{22}N_2O_4$			8·5					8·6		
5	$C_6H_4·NH_2$-*p*	Base	90	68—69	Et_2O	$C_{18}H_{24}N_2O_2$	72·05	8·15	9·2			72·0	8·05	9·3		
5	$C_6H_3(NH_2)_2$-2,4	Base	71	99—100	EtOH–Pet	$C_{18}H_{25}N_3O_2$	68·9	8·25	13·2			68·5	8·0	13·3		
3	CH:CHPh-*trans*	Base	94 [h]	90—92	EtOH–H_2O	$C_{18}H_{21}NO_2$	76·6	7·45	4·8			76·3	7·5	4·9		
		$Me·SO_3H$		188—190	EtOH–Et_2O	$C_{19}H_{21}NO_5S,CH_4O_3S$			3·6	8·4				3·7	8·4	
3	$CH:CH·C_6H_4Me$-*p*-*trans*	Base	88 [h]	104—105	EtOH–H_2O	$C_{19}H_{23}NO_2$	76·9	8·1	4·65			76·7	7·8	4·7		
3	$CH:CH·C_6H_4OMe$-*p*-*trans*	Base	88 [h]	117—118	EtOH	$C_{19}H_{23}NO_3$	76·65	7·7	4·5			72·8	7·35	4·5		
1	1-Naphthyl	Base	65	61—63	Et_2O	$C_{18}H_{17}NO_2$	77·05	6·5	5·3			77·4	6·1	5·0		
		$Me·SO_3H$		192—194	EtOH	$C_{19}H_{17}NO_5S,CH_4O_3S$			3·6	8·5				3·7	8·5	
1	$C_6H_4·SO_3Me$-*p*	Base	85	130	OH·$[CH_2]_2$·OEt–Et_2O	$C_{18}H_{17}NO_4S$			4·6	10·5				4·6	10·4	
1	OMe	Base	80	61—62	EtOH–Et_2O	$C_{13}H_{13}NO_2$	58·6	7·2	7·85			59·0	7·15	7·6		
5	OMe	Base	78	[q]		$C_{19}H_{31}NO_2$	65·05	8·95	5·9			65·3	8·8	5·9		
		$Me·SO_3H$	88	124—126	EtOH–Et_2O	$C_{19}H_{31}NO_5S,CH_4O_3S$			4·2	9·4				4·2	9·6	
2	$O·CH_2Ph$	Base	88	41—42	EtOH–Pet	$C_{16}H_{19}NO_2$	70·1	7·1	5·2			70·3	7·0	5·1		
		$Me·SO_3H$		138—139	EtOH–Et_2O	$C_{16}H_{19}NO_5S,CH_4O_3S$			3·6	8·6				3·8	8·7	
5	OCH_2Ph	Base	80	34—35	Pet [r]	$C_{19}H_{25}NO_2$	72·1	8·0	4·5			72·3	7·9	4·45		
		$Me·SO_3H$		122—124	EtOH–Et_2O	$C_{19}H_{25}NO_5S,CH_4O_3S$			3·1	7·9				3·4	7·8	
2	OPh	Base	84	106—107	EtOH	$C_{15}H_{17}NO_2$	69·3	6·5	5·5			69·5	6·6	5·45		
3	OPh	Base	81	76—78	EtOH	$C_{16}H_{19}NO_2$	70·3	6·85	5·25			70·3	7·0	5·1		
4	OPh	Base	74	115—117	EtOH	$C_{17}H_{21}NO_2$	70·9	7·3	4·9			71·1	7·3	4·9		
5	OPh	Base	81	47—48	$CHCl_3$–Pet	$C_{18}H_{23}NO_2$	71·45	7·5	4·6			71·7	7·7	4·65		
		$Me·SO_3H$	83	125	EtOH–Et_2O	$C_{19}H_{23}NO_5S,CH_4O_3S$			3·5					3·5		
6	OPh	Base	75	104—104·5	EtOH	$C_{19}H_{25}NO_2$	72·55	8·2	4·5			72·4	7·9	4·4		
7	OPh	Base	73	57—58	EtOH	$C_{20}H_{27}NO_2$	73·2	8·5	4·4			73·0	8·2	4·3		
8	OPh	Base	78	76—77	CCl_4	$C_{21}H_{29}NO_2$	73·5	8·5	4·1			73·5	8·5	4·1		
3	$O·C_6H_4·OMe$-*p*	Base	79	66—67·5	EtOH	$C_{17}H_{21}NO_3$	67·1	7·0	4·9			67·3	7·0	4·6		
4	$O·C_6H_4·OMe$-*p*	Base	74	105—107	EtOH	$C_{18}H_{23}NO_3$	67·75	7·25	4·5			68·1	7·3	4·4		
5	$O·C_6H_4·NHAc$-*p*	$Me·SO_3H$	74	167—169	EtOH	$C_{20}H_{26}N_2O_4,CH_4O_3S$ [s]			6·1	7·3				6·2	7·05	
5	$O·C_6H_4·NH_2$-*p*	2$Me·SO_3H$	64	232—234	EtOH	$C_{18}H_{24}N_2O_2,2CH_4O_3S$			5·6	13·05				5·5	12·6	
5	Phthalimido	Base	61	103—105	EtOH	$C_{20}H_{23}NO_4$			7·9					7·9		
		$Me·SO_3H$	92	205—207	EtOH–Et_2O	$C_{20}H_{23}NO_4,CH_4O_3S$			6·0					6·2		
6	Phthalimido	Base	98	86—87	EtOH	$C_{21}H_{25}NO_4$	68·4	6·75	7·9			68·4	6·6	7·6		
8	Phthalimido	Base	82	70—71	EtOH	$C_{23}H_{29}NO_4$	69·6	7·05	7·1			69·7	7·1	7·1		
5	NH·COPh	Base	82	103—104	C_6H_6	$C_{19}H_{18}N_2O_3$	69·6	7·7	8·6			69·5	7·3	8·5		
5	$NH·CO·CH_2·NHBz$	Base	61	120·5—121·5	C_6H_6	$C_{21}H_{23}N_3O_4$	65·3	7·3	10·8			65·4	7·0	10·9		
5	Glutarimido	Base	83	94—95	EtOH	$C_{17}H_{24}N_2O_4$	63·5	7·0	8·85			63·8	7·5	8·8		
5	Phthalimidino	Base	76 [t]	129—130	EtOH	$C_{20}H_{24}N_2O_2$	70·3	7·0	8·3			70·55	7·1	8·2		
1	CHPh·OH	Base	51 [u]	96—97	EtOH–H_2O	$C_{15}H_{17}NO$	69·1	6·3	5·3			69·5	6·6	5·4		
4	CHPh·OH	Base	73 [u]	104—105	EtOH	$C_{19}H_{23}NO_2$	71·8	7·7	4·7			71·7	7·7	4·65		
6	CHPh·OH	Base	89 [u]	108—110	EtOH	$C_{20}H_{27}NO_2$	72·6	8·05	4·2			72·95	8·3	4·3		
4	CHPh·OAc	Base	72	67—68	Et_2O	$C_{23}H_{25}NO_4$	70·15	7·5	4·1			70·0	7·3	4·1		
6	CHPh·OAc	Base	74	36—37	Et_2O–Pet [v]	$C_{25}H_{29}NO_4$	71·4	8·1	3·9			71·15	7·85	3·8		
4	COPh	Base	61 [v]	101—103	MeOH	$C_{16}H_{21}NO_3$	72·1	7·0	4·7			72·3	7·0	4·7		

TABLE 2. (*Continued.*)

			Yield				Found (%)					Required (%)				
n	R	Derivative	(%)	M. p.	Solvent [a]	Formula	C	H	N	S	Hal	C	H	N	S	Hal
6	COPh	Base	83 [g]	85—87°	EtOAc–Et_2O	$C_{20}H_{21}NO_2$	73·0	7·9	4·2			73·4	7·65	4·3		
4	$CHPh(OEt)_2$	Base	78	107—109	MeOH	$C_{22}H_{31}NO_4$	71·2	8·65	3·7			70·8	8·3	3·75		
5	SMe	Base	58 [h]	53·5—56	EtOH–H_2O	$C_{12}H_{21}NO_2S$			5·3					5·5		
5	$S[CH_2]_2{\cdot}OH$	Base	41 [h]	38—40	Et_2O	$C_{14}H_{23}NO_3S$			5·1	11·25				4·9	11·2	
3	$S{\cdot}CH_2Ph$	$Me{\cdot}SO_3H$	62 [h]	134—136	MeOH	$C_{17}H_{21}NO_5S_2,CH_4O_3S$			3·3	15·95				3·5	16·1	
3	SPh	Base	75 [h]	57—58	EtOH–Et_2O	$C_{16}H_{19}NO_2S$			4·7	11·0				4·8	11·1	
5	SPh	Base	74 [h]	72—73	EtOH–H_2O	$C_{18}H_{23}NO_2S$	68·0	7·1		9·9		68·1	7·3		10·1	
5	$S{\cdot}C_6H_4Cl$-*p*	Base	81 [h]	44—46	Et_2O–Pet	$C_{18}H_{20}ClNO_2S$			4·0		9·9			4·0		10·1
5	SO_2Me	Base	87	84—87	MeOH	$C_{12}H_{21}NO_4S$	54·5	7·2		11·35		54·4	7·3		11·15	
5	SO_2Ph	Base	73	89—90	EtOH	$C_{18}H_{23}NO_4S$	62·0	7·0		9·0		61·8	6·65		9·2	

[a] Solvent for recrystn. Pet = light petroleum (b. p. 40—60°, except where stated) [b] Lit.,[8] m. p. 55°. [c] Diptolate = di-*p*-toluoyl-D-tartrate. [d] Overall from potassium nitroguaiacyl oxide. [e] B. p. 143—146°/0·05 mm. [f] B. p. 160—170°/0·2 mm. [g] B. p. 60—80°. [h] Reduction by sodium sulphide in ethanol. [i] From the corresponding nitro-ketone. [j] By acid hydrolysis of the acetate (cf. ref. 3). [k] B. p. 100—120°. [l] Overall from 4-phenylbutyl bromide. [m] From 1-(2-methoxy-4-nitrophenoxy)-5-phenylpentane. [n] From 1-(2-methoxy-4-nitrophenoxy)-5-phenylpent-4-ene. [o] Overall from 6-phenylhexanol. [p] From the *N*-acetyl derivative by hydrolysis with 2N-aqueous hydrochloric acid in ethanol. [q] B. p. 160—165°/0·1 mm. [r] B. p. 80—100°. [s] Found: OMe, 6·85. Required: OMe, 6·8%. [t] From the corresponding phthalimide by reduction with tin and hydrochloric acid (see Part III [1]). [u] From the corresponding nitro-ketone. [v] By reduction of the nitro-ketone with iron–acetic acid.

TABLE 3. p-*Aminophenyl ethers,* $p\text{-}NH_2{\cdot}C_6H_4{\cdot}O{\cdot}[CH_2]_n{\cdot}R$.

			Yield				Found (%)				Required (%)			
n	R	Derivative	(%)	M. p.	Solvent	Formula	C	H	N	S	C	H	N	S
4	COPh	Base	49 [b]	112—114°	EtOH	$C_{17}H_{19}NO_2$	75·9	7·0	5·25		75·9	7·1	5·2	
5	COPh	Base	56 [b]	61—63	C_6H_6–Pet [c]	$C_{18}H_{21}NO_2$	76·2	7·3	5·0		76·4	7·4	4·95	
5	$CHPh{\cdot}OH$	Base	89 [d]	86—88	Et_2O–Pet	$C_{18}H_{23}NO_2$	75·8	8·2	4·95		75·8	8·1	4·9	
5	SPh	Base	92 [e]	63	C_6H_6–Pet	$C_{18}H_{21}NOS$			4·75	11·5			4·9	11·2
5	$S{\cdot}C_6H_4{\cdot}NH_2$-*p*	2HCl	66 [e]	220—230 (decomp.)	Dil. HCl	$C_{17}H_{22}N_2OS,2HCl$			7·3	8·55			7·5	8·5
5	$S{\cdot}CH_2Ph$	$Me{\cdot}SO_3H$	91 [e]	147—149	EtOH–Et_2O	$C_{18}H_{23}NOS,CH_4O_3S$			3·5	16·3			3·5	16·1
5	SOPh	Base	65 [e]	70—71	Et_2O	$C_{17}H_{21}NO_2S$	67·1	7·1	4·5		67·3	6·9	4·6	
5	$SO{\cdot}CH_2Ph$	Base	66 [e]	89—90	Et_2O	$C_{18}H_{23}NO_2S$			4·5	10·45			4·4	10·1
5	SO_2Ph	Base	82	93—95	EtOH	$C_{17}H_{21}NO_3S$			4·4	9·9			4·4	10·0
5	$SO_2{\cdot}C_6H_4{\cdot}NH_2$-*p*	Base	84	136—138	EtOH	$C_{17}H_{22}N_2O_3S$			8·0	9·7			8·4	9·6
		Diacetyl		154		$C_{21}H_{26}N_2O_5S$			6·6				6·7	
5	$SO_2{\cdot}C_6H_4{\cdot}NHAc$-*p*	Base	87	126—128	EtOH	$C_{19}H_{24}N_2O_4S$	60·2	6·4	7·4		60·6	6·4	7·45	
5	$SO_2{\cdot}CH_2Ph$	Base	94	101—102	EtOH	$C_{18}H_{23}N_4O_4S$			4·1	9·9			4·2	9·6

[a] Solvent for recrystn. Pet = light petroleum. [b] Nitro-ketone reduced with iron in 90% acetic acid. [c] B. p. 60—80°. [d] By catalytic reduction of either the nitro-ketone or nitro-alcohol. [e] Reduction by sodium sulphide in ethanol. [f] B. p. 80—100°.

TABLE 4. *N-Substituted amines*, $R''R'N$ (C$_6$H$_3$OMe)$O\cdot[CH_2]_n\cdot R$

R′	R″	*n*	R	Deriv.	Yield (%)	M. p.	Solvent [a]	Formula	Found (%) C	H	N	Hal	Required (%) C	H	N	Hal
Me	H	5	Ph	Base	63	35° [b]	Et_2O–Pet	$C_{19}H_{31}NO_2$	76·6	8·6	4·7		76·2	8·4	4·7	
Me	H	7	Me	Base	63	[c]		$C_{16}H_{27}NO_2$	72·5	10·2	5·2		72·5	10·2	5·3	
Me	Me	2	Ph	Base	93	32—33	Et_2O	$C_{17}H_{21}NO_2$	75·3	7·7	5·3		75·3	5·75	5·2	
				MeI	89	152—156	H_2O	$C_{18}H_{24}INO_2$			3·5	30·6			3·4	30·8
Me	Me	5	Ph	Base	93	38·5—39·5	Et_2O–Pet	$C_{20}H_{27}NO_2$	76·9	8·5	4·2		76·6	8·7	4·5	
				MeI	93	183—185	H_2O	$C_{21}H_{30}INO_2$			2·8	27·6			3·1	27·9
				p-C$_6$H$_4$Me·SO$_3$H		114—116	EtOH–Et_2O	$C_{20}H_{27}NO_2,C_7H_8O_3S$	66·3	7·4	2·6	6·5 [d]	66·8	7·3	2·9	6·6 [d]
Me	Me	7	Me	HBr	80	119—120	EtOH–Et_2O	$C_{17}H_{30}NO_2,HBr$			3·9	22·1			3·9	22·2
				MeI	67	184—186 (decomp.)	H_2O	$C_{18}H_{32}INO_2$			3·0	30·6			3·3	30·1
Me	Me	4	OPh	Base	89	49—51	Et_2O–Pet	$C_{19}H_{25}NO_2$	72·5	8·2	4·5		72·35	8·0	4·4	
				MeI	95	162·5—164 (decomp.)	H_2O	$C_{20}H_{28}INO_2$			3·05	27·1			3·1	27·8
Me	Me	4	COPh	Base	73	82—84	EtOH	$C_{20}H_{25}NO_2$	73·2	7·9	4·3		73·45	7·6	4·3	
				MeI	92	160—163 (decomp.)	H_2O	$C_{21}H_{28}INO_2$			3·0	27·0			3·0	27·1
Me	Me	5	SPh	HBr	26	96—98	Aq. HBr	$C_{20}H_{27}NO_2S,HBr$			3·2	19·0			3·3	18·7
				MeI	100	142—145 (decomp.)	H_2O	$C_{21}H_{30}INO_2S$			2·8	25·95			2·9	26·1
Me	Me	5	*p*-C$_6$H$_4$NMe$_2$	Base	74	39—41	Pet	$C_{29}H_{32}N_2O_2$	74·1	9·05	7·8		74·1	9·05	7·9	
				MeI	80	203—204	H_2O	$C_{24}H_{33}IN_2O_2$			4·3	39·5			4·4	39·6
Me	Me	5	Phthalimido	Base	92	70—72	EtOH	$C_{23}H_{26}N_2O_4$	69·1	7·0	7·4		69·1	6·85	7·3	
				MeI	100	200—202	H_2O	$C_{24}H_{29}IN_2O_4$			5·1	23·6			5·35	24·2
Et	Et	7	Me	Base	85 [e]			$C_{19}H_{33}NO_2$	74·3	10·8	4·9		74·2	10·8	4·6	
CO_2·CH_2·CH_2Cl	H	2	Ph		90	63—65	EtOH	$C_{18}H_{28}ClNO_4$			4·0	10·3			4·0	10·1
CO_2·CH_2·CH_2Cl	H	7	Me		100	72—73·5	EtOH	$C_{19}H_{32}ClNO_4$			3·8	9·75			3·9	9·9
CO_2·CH_2·CH_2Cl	H	4	OPh		94	109—110	EtOH	$C_{20}H_{24}ClNO_5$			3·5	8·9			3·6	9·0
CO_2CH_2·CH_2Cl	H	4	COPh		69	95—97	EtOH	$C_{21}H_{24}ClNO_5$			3·4	8·6			3·45	8·75
CO_2CH_2·CH_2Cl	H	5	SPh		86	45—47	EtOH–H_2O	$C_{21}H_{26}ClNO_4S$				8·15				8·4
$[CH_2]_2$·OH	H	2	Ph	HBr	75	147·5—149	MeOH–Et_2O	$C_{17}H_{23}NO_2,HBr$			3·8	21·5			3·8	21·7
$[CH_2]_2$·OH	H	7	Me	Base	75	35—36	Pet	$C_{17}H_{29}NO_2$			4·8				4·75	
$[CH_2]_2$·OH	H	4	OPh	Base	87	62·5—63·5	MeOH	$C_{19}H_{23}NO_4$	68·5	7·8	4·2		68·8	7·6	4·2	
$[CH_2]_2$·OH	H	4	COPh	Base	86	77—78	EtOH–Et_2O	$C_{20}H_{21}NO_4$	70·2	7·45	4·1		70·0	7·3	4·1	
$[CH_2]_2$·OH	H	5	SPh	HBr	67	113—115	EtOH–Et_2O	$C_{20}H_{27}NO_2S,HBr$			3·1	17·85			3·2	18·1
$[CH_2]_2$·OH	$[CH_2]_2$·OH	7	Me	Base	34	62—64	Et_2O	$C_{19}H_{33}NO_4$	67·2	9·9	4·3		67·2	9·8	4·1	
$[CH_2]_2$·OH	$[CH_2]_2$·OH	5	Phthalimido	Base	51	68—69	EtOH	$C_{24}H_{28}N_2O_6$	64·9	6·8	6·2		65·2	6·8	6·3	

[a] Solvent for recrystn. Pet = light petroleum. [b] B. p. 197—228°/0·04 mm. [c] B. p. 161—163°/0·2 mm. [d] Sulphur analysis. [e] Overall from primary amine; intermediate quaternary salt not isolated. [f] B. p. 162—174°/0·05 mm.

2,6-*Dimethoxy*-4-*nitrophenol*.—(*a*) The foregoing nitro-compound (60 g.) was stirred and refluxed for 2 days with potassium hydroxide (60 g.) in water (350 ml.), then cooled. The potassium salt (49·5 g., 74%) was filtered off, washed with chloroform and ethanol, and dried. The mother-liquors were concentrated and refluxed for a further 24 hr., giving a second crop (6·1 g., 9%). The sodium salt was similarly obtained.

(*b*) A mixture of 1,3-dimethoxyacetone (7·14 g.), sodium nitromalondialdehyde (9·5 g.), and a solution of sodium hydroxide (0·9 g.) in water (90 ml.) was kept overnight at room temperature, then concentrated *in vacuo*, cooled, and filtered, giving the sodium salt (8·35 g., 62%) of the phenol. Acidification and recrystallisation from aqueous acetic acid gave 2,6-*dimethoxy*-4-*nitrophenol*, m. p. 136—137° (effervescence) (Found: N, 6·8; OMe, 30·7. $C_8H_9NO_5$ requires N, 7·0; OMe, 31·2%).

1-(2,6-*Dimethoxy*-4-*nitrophenoxy*)-5-*phthalimidopentane*.—A mixture of potassium 2,6-dimethoxy-4-nitrophenoxide (40 g.), 5-phthalimidopentyl bromide (50 g.), and 2-ethoxyethanol (100 ml.) was stirred under reflux at 100° for 7 days. The product crystallised from ethanol, yielding the 5-*phthalimidopentyl ether* (68%), m. p. 105—106° (Found: N, 6·75; OMe, 15·2. $C_{21}H_{22}N_2O_7$ requires N, 6·75; OMe, 14·9%). Similarly obtained (63%) (refluxed for 48 hr.) was 1-(2,6-*dimethoxy*-4-*nitrophenoxy*)-5-*phenylpentane*, m. p. 36—37° (from light petroleum) (Found: C, 66·6; H, 6·9; N, 4·4. $C_{19}H_{23}NO_5$ requires C, 66·1; H, 6·7; N, 4·1%).

The nitro-compounds listed in Table 1 were prepared (except where stated) by condensation of potassium 2-methoxy-4-nitrophenoxide with the appropriate alkyl or substituted alkyl bromide, usually in boiling ethanol or 2-ethoxyethanol.

Amines.

Di-[5-(4-*amino*-2-*methoxyphenoxy*)*pentyl*] *Sulphide*.—A mixture of 5-(2-methoxy-4-nitrophenoxy)pentyl bromide (24 g.), sodium sulphide nonahydrate (48 g.), ethanol (200 ml.), and water (100 ml.) was stirred and refluxed for 24 hr. The ethanol was distilled off and the residue was shaken with ether. The solid (4·55 g., 27%; m. p. 81—89°) which separated was dissolved in chloroform and shaken with 2N-hydrochloric acid. The hydrochloride was reconverted into the *base* which, after recrystallisation from chloroform–ether, had m. p. 90—92° (Found: N, 6·2; S, 7·1. $C_{24}H_{36}N_2O_4S$ requires N, 6·2; S, 7·1%).

3,3′-*Dimethoxy*-4,4′-*di*-n-*octyloxyazoxybenzene*.—This *compound*, m. p. 86—89° (from 2-ethoxyethanol) (Found: C, 70·1; H, 9·1; N, 5·2%; *M*, 490. $C_{30}H_{46}N_2O_5$ requires C, 70·0; H, 8·95; N, 5·45%; *M*, 514), separated (5% yield) on one occasion when a batch of 1-(2-methoxy-4-nitrophenoxy)octane was reduced over Raney nickel in ethanol. The principal product, 3-methoxy-4-octyloxyaniline, was isolated from the filtrate.

4-*Amino*-2-*methoxyphenyl* D-*Glucoside*.—The corresponding nitro-compound (15·6 g.) in ethanol (460 ml.) and water (180 ml.) was reduced over Raney nickel. Concentration of the filtered solution and recrystallisation of the solid from ethanol gave the *amine* (70%), m. p. 202—203°, $[\alpha]_D^{19.5}$ −61° in H_2O (Found: C, 51·7; H, 6·3; N, 4·7. $C_{12}H_{19}NO_7$ requires C, 51·8; H, 6·3; N, 4·65%).

3,5-*Dimethoxy*-4-5′-*phthalimidopentylaniline* was obtained (85%) by catalytic reduction of the nitro-compound over Raney nickel in dimethylformamide. After crystallisation from ethanol, it had m. p. 97° (Found: C, 65·7; H, 6·35; N, 7·45. $C_{21}H_{24}N_2O_5$ requires C, 65·6; H, 6·3; N, 7·3%). 3,5-*Dimethoxy*-, m. p. 85—87° (from ether) (Found: C, 72·5; H, 8·0; N, 4·4. $C_{19}H_{25}NO_3$ requires C, 72·4; H, 7·9; N, 4·4%), and 3-*methoxy*-4-5′-*phenylpentyloxyaniline* (92%), m. p. 59—60° (from ether–light petroleum) (Found: C, 75·7; H, 8·3; N, 4·9. $C_{18}H_{23}NO_2$ requires C, 75·75; H, 8·1; N, 4·9%) [*methanesulphonate*, m. p. 130—131° (from ethanol–ether) (Found: N, 3·55; S, 8·4. $C_{18}H_{23}NO_2,CH_4O_3S$ requires N, 3·7; S, 8·4%)], were obtained (90%) by a similar reduction in ethanol.

The primary amines listed in Tables 2 and 3 were prepared (except where stated) by catalytic reduction of the corresponding nitro-compounds, usually over Raney nickel in ethanol or 2-ethoxyethanol, but occasionally in ethyl acetate or dimethylformamide.

N-*Formyl*-3-*methoxy*-4-5′-*phenylpentyloxyaniline*, prepared (89%) from the primary amine by means of formamide and concentrated hydrochloric acid [1] and recrystallised from methanol, had m. p. 86—88° (Found: C, 72·9; H, 7·2; N, 4·4. $C_{19}H_{23}NO_3$ requires C, 72·8; H, 7·4; N, 4·5%). The 4-*octyloxy*-*derivative* (81%), m. p. 77—78° (from methanol) (Found: C, 68·3; H, 9·1; N, 4·95. $C_{16}H_{25}NO_3$ requires C, 68·8; H, 9·0; N, 5·0%), was similarly prepared.

N-Methyl Derivatives (Table 4).—The foregoing formamides were reduced with lithium aluminium hydride in ether–benzene.

NN-Dimethyl and NN-Diethyl Derivatives (Table 4).—The primary amines were converted into the quaternary iodides, which were pyrolysed under reduced pressure (see Part III [1]).

N-(2-Chloroethoxycarbonyl)-3-methoxy-4-5′-phenylpentyloxyaniline.—2-Chloroethyl chloroformate (8·7 g.) and sodium acetate trihydrate (11·1 g.) were added successively to a suspension of 3-methoxy-4-5′-phenylpentyloxyaniline (20 g.) in water (115 ml.) and acetic acid (3 ml.). The mixture was periodically shaken during 1 hr., then filtered, and the solid was washed with water and recrystallised from aqueous ethanol, giving the *urethane* (85%), m. p. 76—78·5° (Found: N, 3·6; Cl, 8·95. $C_{21}H_{26}ClNO_4$ requires N, 3·6; Cl, 9·1%). The other *urethanes* listed in Table 4 were similarly obtained.

N-(2-Hydroxyethyl)-3-methoxy-4-5′-phenylpentyloxyaniline.—The foregoing urethane (22·4 g.) was added to a solution of sodium hydroxide (12 g.) in water (23 ml.), ethanol (4·9 ml.), and 2-ethoxyethanol (49 ml.), and the mixture was refluxed for 10 min., cooled, diluted with water, and filtered. The product was washed with water and recrystallised from aqueous ethanol, giving the *amine* (68%), m. p. 72—73° (Found: C, 73·05; H, 8·35; N, 4·3. $C_{20}H_{27}NO_3$ requires C, 73·0; H, 8·2; N, 4·3%). The other N-2-*hydroxyethyl derivatives* (Table 4) were similarly prepared.

NN-Di-(2-hydroxyethyl)-3-methoxy-4-5′-phenylpentyloxyaniline.—A mixture of 3-methoxy-4-5′-phenylpentyloxyaniline (14·27 g.), calcium carbonate (14·27 g.), ethylene chlorohydrin (14·27 ml.), and water (150 ml.) was stirred and refluxed for 18 hr., cooled, and extracted with chloroform. The extract was evaporated and the residue treated with methanesulphonic acid in ethanol–ether. After recrystallisation from ethanol–ether, the *methanesulphonate* (46%) of the tertiary amine had m. p. 93—94° (Found: N, 2·9; S, 6·8. $C_{32}H_{31}NO_4.CH_4O_3S$ requires N, 3·0; S, 6·8%). The other *di-(2-hydroxyethyl) derivatives* (Table 4) were similarly prepared.

NN-Di-(2-hydroxypropyl)-3-methoxy-4-5′-phthalimidopentyloxyaniline.—A mixture of 3-methoxy-4-5′-phthalimidopentyloxyaniline (20 g.), 1,2-epoxypropane (25 ml.), ethanol (170 ml.), and concentrated hydrochloric acid (1 ml.) was refluxed for 24 hr., diluted with water, and filtered. Recrystallisation of the solid from methanol–ether gave the tertiary *amine* (28%), m. p. 112—114° (Found: C, 66·5; H, 7·3; N, 6·3. $C_{26}H_{34}N_2O_6$ requires C, 66·4; H, 7·7; N, 6·0%).

N-D-Glucosyl-3-methoxy-4-5′-phthalimidopentyloxyaniline.—A mixture of 3-methoxy-4-5′-phthalimidopentyloxyaniline (3·54 g.), D-glucose (1·8 g.), and ethanol (30 ml.) was refluxed for 1·5 hr. (a clear solution was formed after 1 hr.), then concentrated to 15 ml., cooled, and filtered. The *glucosylamine* (53%) had m. p. 121—123° (Found: C, 59·2; H, 6·5; N, 5·35; H_2O, 1·8. $C_{26}H_{33}N_2O_9.0{\cdot}5H_2O$ requires C, 59·4; H, 6·3; H, 5·3; H_2O, 1·7%). Similarly prepared (62%) was the *galactosylamine*, m. p. 96—98° (Found: C, 60·1; H, 6·6; N, 5·7. $C_{26}H_{32}N_2O_9$ requires C, 60·5; H, 6·2; N, 5·4%).

4,6-Diamino-1,2-dihydro-1-(3-methoxy-4-octyloxyphenyl)-2,2-dimethyl-1,3,5-triazine.—A mixture of 3-methoxy-4-octyloxyaniline (30 g.), dicyandiamide (10 g.), concentrated hydrochloric acid (10 ml.), and acetone (300 ml.) was refluxed for 4 hr., cooled, and filtered, and the residue was washed with acetone. The *triazine hydrochloride* had m. p. 210—212° (Found: N, 17·0; Cl, 8·55. $C_{20}H_{33}N_5O_2.HCl$ requires N, 17·0; Cl, 8·6%).

The authors thank Dr. H. J. Barber, F.R.I.C., and Dr. J. N. Ashley, F.R.I.C., for their continued interest, and Mr. S. Bance, F.R.I.C., for the analyses.

THE RESEARCH LABORATORIES, MAY AND BAKER LTD.,
DAGENHAM, ESSEX.

[*Received, October 24th*, 1960.]

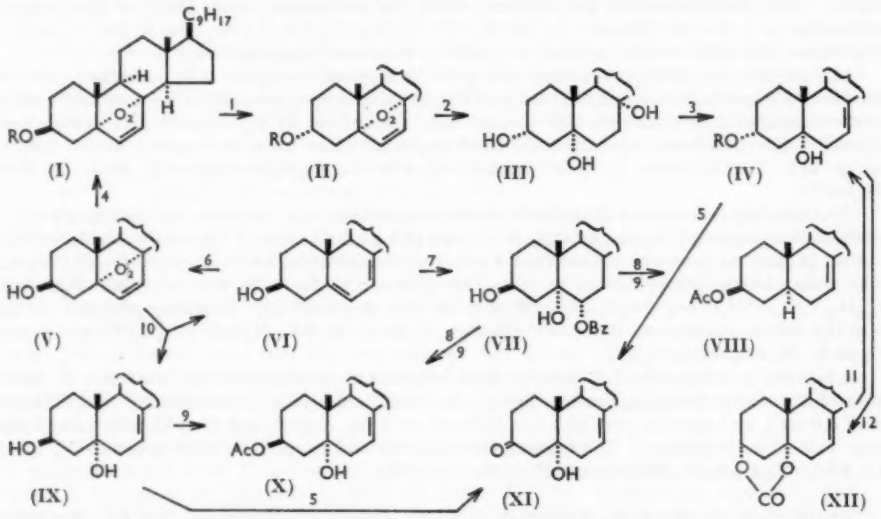
XUM

364. *Proof of Rear Approach in the Oxidation of Ergosterol.*

By F. Dalton and G. D. Meakins.

Many products obtained by oxidation of the ring B diene system in ergosterol have been formulated as arising from rear approach to the less hindered (α) side of the molecule. The present work provides chemical proof of the α-configuration of the 5-hydroxyl group in one of these products (the triol monobenzoate formed by oxidising ergosterol with perbenzoic acid).

In deducing the stereochemistry of products formed from steroids frequent use has been made of the "rule of rear attack," that certain reagents usually approach the steroid molecule from the less hindered (α) side.[1] Many exceptions to the rule are met even with natural steroids, especially when addition to ring A or B is involved,[2] and the rule is not applicable when the basic steroid stereochemistry is modified.[3] Results expected from the rule have been confirmed in some cases, such as the α-epoxidation of cholesterol,[4] by direct proof of the structures of the products. Elsewhere the stereochemical details are inferred by analogy, and the main support for the structures so deduced is that they lead to satisfactory explanations of the relations between the products. The series of compounds [1] formed by oxidising the 5,6-double bond of ergosterol and ergosteryl acetate fall into the latter category. While the accepted structures of the products are in accord with



Reagents: 1, Al_2O_3–KOH. 2, H_2–Pt. 3, HCl–MeOH. 4, p-$C_6H_4Me{\cdot}SO_2Cl$–C_5H_5N. 5, CrO_3–$COMe_2$. 6, O_2, irradiation. 7, BzO_2H–$CHCl_3$. 8, Li–NH_2Et. 9, Ac_2O–C_5H_5N. 10, $LiAlH_4$. 11, KOH–MeOH. 12, $COCl_2$–C_5H_5N.

their reactions and are supported by molecular-rotation data [5] there is no chemical proof that they arise by oxidation at the α-face of ergosterol and ergosteryl acetate.

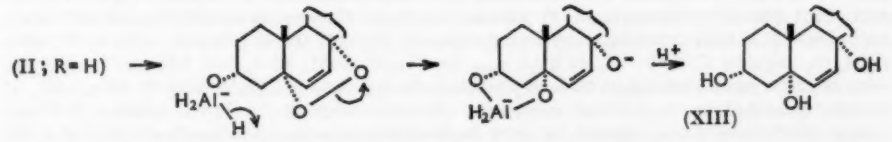
In the present work the α-orientation of the 5-hydroxyl group in the triol monobenzoate (VII) (obtained by oxidising ergosterol with perbenzoic acid [6]) was established by the

[1] For references see Fieser and Fieser, "Steroids," Reinhold Publ. Co., New York, 1959, pp. 14, 98.
[2] See, *inter al.*, Petrow, Rosenheim, and Starling, *J.*, 1943, 135; Henbest and Wilson, *J.*, 1956, 3289; Corey and Sneen, *J. Amer. Chem. Soc.*, 1956, **78**, 6289.
[3] Castells, Fletcher, Jones, Meakins, and Swindells, *J.*, 1960, 2627, and subsequent papers.
[4] Plattner and Lang, *Helv. Chim. Acta*, 1944, **27**, 1872.
[5] Zürcher, Heusser, Jeger, and Geistlich, *Helv. Chim. Acta*, 1954, **37**, 1562; Mills, *J.*, 1952, 4976.
[6] Windaus and Lüttringhaus, *Annalen*, 1930, **481**, 119.

following method, the 3β-hydroxyl group of ergosterol being used as a reference point. After inversion of the 3β-hydroxyl group in a suitable derivative of ergosterol, *i.e.*, the 5,8-epidioxide (V), the product was converted into the 3,5-diol (IV; R = H). In this diol the *cis*-orientation of the hydroxyl groups (and therefore the α-configuration of the 5-hydroxyl group) was demonstrated by the formation of a cyclic carbonate (XII). Oxidation of the diol gave the 5-hydroxy-3-ketone (XI). This hydroxy-ketone was also obtained by a route which related it to the triol monobenzoate, thus establishing the presence of a 5α-hydroxyl group in the latter compound. A somewhat similar sequence was used to establish the preference for attack at the β-face in the oxidation of lumisterol.[7]

In view of the failure of attempts [8] to epimerise the hydroxyl group of ergosterol itself the hydroxy-epidioxide [9] (V) in which the ring B diene system is masked was chosen as starting material: the epidioxide bridge is stable to the alkaline conditions used in the epimerisation of the 3-hydroxyl group, and is suitable for the production of a 5-hydroxyl group at a later stage. On treatment with alumina impregnated with potassium hydroxide [10] the corresponding toluene-*p*-sulphonate (I; R = *p*-$C_6H_4Me{\cdot}SO_2$) gave a new hydroxy-epidioxide (yield 43% after allowance for recovered toluene-*p*-sulphonate) which gave an acetoxy-epidioxide under mild conditions. The method of preparation and properties of these compounds show them to be the 3α-hydroxy- and 3α-acetoxy-epidioxides (II; R = H and Ac, respectively).

Reduction of the 3β-hydroxy-epidioxide (V) with lithium aluminium hydride followed by acetylation of the product yields the 3β-acetoxy-5α-hydroxy-compound (X) and ergosteryl acetate.[11] It was hoped that reduction of the 3α-hydroxy-epidioxide would similarly give the required 3α,5α-diol (IV; R = H), but the major product was a triol formulated as the 3α,5α,8α-trihydroxy-compound (XIII). [Only one of the triol's hydroxyl groups was acetylated on treatment with acetic anhydride in pyridine at 20°. The triol was also obtained from the 3α-hydroxy-epidioxide by reduction with zinc and methanolic sodium hydroxide, conditions which are known to convert the 3β-hydroxy-epidioxide (V) into the epimeric 3β,5α,8α-triol.[1] These facts, together with the α-orientation of the epidioxide bridge (see below), establish the structure of triol (XIII).] The preferential formation of the $\Delta^{6,22}$-3,5,8-triol (rather than the $\Delta^{7,22}$-3,5-diol) in the reduction of the 3α-hydroxy-epidioxide (II; R = H) with lithium aluminium hydride may be attributed to the proximity of the 3-hydroxyl and epidioxide groups, fission of the O–O bond occurring as in the annexed scheme.



(XIII)

The required $\Delta^{7,22}$-3,5-diol (IV; R = H) was obtained from the 3α-hydroxy-epidioxide (II; R = H) by an alternative route which involved hydrogenation of the epidioxide in ethyl acetate to the Δ^{22}-3,5,8-triol (III) and dehydration of this compound with methanolic hydrogen chloride. (Similar treatment of the 3β-hydroxy-epidioxide gives the $\Delta^{7,22}$-3β,5α-diol.[12]) Proof that the diol (IV; R = H) is a 3,5- rather than a 3,8-dihydroxy-compound follows from results described below: if the positions of the hydroxyl groups are assumed their *cis*-relation is shown by the formation of a cyclic carbonate (XII) from the diol (IV; R = H). [The possibility that carbonyl chloride had coupled two molecules of

[7] Mayor and Meakins, *J.*, 1960, 2792.
[8] Barnett, Heilbron, and Jones, *J.*, 1940, 1390.
[9] Windaus and Brunken, *Annalen*, 1928, **460**, 225.
[10] Douglas, Ellington, Meakins, and Swindells, *J.*, 1959, 1720.
[11] Laws, *J.*, 1953, 4185.
[12] Clayton, Henbest, and Jones, *J.*, 1953, 2015.

XUM

the diol (IV; R = H) to give a " dimeric " carbonate was excluded by a molecular-weight determination.]

Mild oxidation of the diol (IV; R = H), in which the hydroxyl groups are now established to have the α-configuration, afforded the 5α-hydroxy-3-ketone (XI). To complete the work it was necessary to link the hydroxy-ketone (XI) to the triol monobenzoate (VII). Reduction of the latter compound with lithium in ethylamine and acetylation of the products gave mainly 5α-ergosta-7,22-dien-3β-yl acetate (VIII), the required 3β-acetoxy-5α-hydroxy-compound [12] (X) being formed in only low yield. However, the related 3β,5α-diol (IX) was readily obtained [by reduction of the 3β-hydroxy-epidioxide (V) with lithium aluminium hydride], and the acetylation [12] of this diol to the 3β-acetoxy-5α-hydroxy-compound (X) was confirmed. Oxidation of the 3β,5α-diol afforded the 5α-hydroxy-3-ketone (XI) already obtained from the 3α,5α-diol (IV; R = H).

Since the tertiary hydroxyl groups in the triol monobenzoate (VII) and the diol (IX) are known to be at position 5 the corresponding groups in the hydroxy-ketone (XI) and the diol (IV) must occupy the same position. The present work establishes the α-configuration of these groups, and thus confirms the α-orientation of the epidioxide bridge in ergosterol epidioxide (V) originally suggested from the rule of rear attack [1] and later supported by more direct evidence.[12]

Experimental

For general directions see *J.*, 1958, 2156.

5α,8α-Epidioxyergosta-6,22-dien-3α-ol (II; R = H).—Toluene-*p*-sulphonyl chloride (6 g.) was added to a solution of 5α,8α-epidioxyergosta-6,22-dien-3β-ol (V) (8 g.; m. p. 183—186°, $[\alpha]_D$ −35°, prepared directly from ergosterol by the method used in converting ergosteryl acetate into the acetate of the epidioxide [12]) in pyridine (40 ml.) at 0° and the mixture was kept at 0° for 2 days. After addition of water the insoluble material was collected and crystallised from ethanol, to give the *toluene*-p-*sulphonate* (I; R = *p*-$C_6H_4Me\cdot SO_2$) (10 g.) as plates, m. p. with decomp. dependent on rate of heating, $[\alpha]_D$ 0° (*c* 1·3) (Found: C, 71·7; H, 8·4. $C_{35}H_{50}O_5S$ requires C, 72·1; H, 8·65%), $\nu_{max.}$ (in Nujol) 1198, 1180, 971, and 693 cm.$^{-1}$.

The toluene-*p*-sulphonate (10 g.) was adsorbed from benzene on a column of alumina (750 g., impregnated with potassium hydroxide) in the usual way.[10] The solution obtained by elution with ether–methanol (8 : 1; 700 ml.) was washed with water, dried, and evaporated, and the mixture (8·9 g.) so obtained was chromatographed on deactivated alumina (800 g.). Elution with light petroleum–benzene (3 : 2) afforded *5α,8α-epidioxyergosta-2(?),6,22-triene* (210 mg.; m. p. 116—118° after crystallisation from methanol), $[\alpha]_D$ +7° (*c* 1·4) (Found: C, 81·8; H, 10·3. $C_{28}H_{42}O_2$ requires C, 81·9; H, 10·3%), $\nu_{max.}$ (in Nujol) 1031, 1015, and 976 cm.$^{-1}$. Elution with benzene gave unchanged toluene-*p*-sulphonate (I; R = *p*-$C_6H_4Me\cdot SO_2$) (5·18 g.), $[\alpha]_D$ 0° (*c* 1·2), identified by its infrared spectrum. Benzene–ether (9 : 1) eluted material (2·07 g.) which crystallised from ethanol to give *5α,8α-epidioxyergosta-6,22-dien-3α-ol* (II; R = H) (1·52 g.), m. p. 192—195° depressed on admixture with the 3β-alcohol (V), $[\alpha]_D$ −30° (*c* 1·6) (Found: C, 78·3; H, 10·3. $C_{28}H_{44}O_3$ requires C, 78·45; H, 10·35%), $\nu_{max.}$ (in Nujol) 3478, 3425, 1042 sh, 1036, 1013, and 966 cm.$^{-1}$.

Acetylation of the 3α-hydroxy-epidioxide with acetic anhydride–pyridine at 20° afforded the *3α-acetoxy-epidioxide* (II; R = Ac), m. p. 210—213° (from ethanol), $[\alpha]_D$ 0° (*c* 1·6) (Found: C, 76·6; H, 10·0. $C_{30}H_{46}O_4$ requires C, 76·6; H, 9·85%), $\nu_{max.}$ (in Nujol) 1730, 1266, 1241, and 965 cm.$^{-1}$.

Reduction of 5α,8α-Epidioxyergosta-6,22-dien-3α-ol (II; R = H).—(a) *With lithium aluminium hydride.* A solution of the hydroxy-epidioxide (800 mg.) in ether (100 ml.) was refluxed with lithium aluminium hydride (650 mg.) for 2 days. After addition of ethyl acetate and then 2N-sulphuric acid the products were isolated with ethyl acetate and chromatographed on deactivated alumina (100 g.). Benzene eluted material (260 mg.) which was repeatedly crystallised from acetone and then sublimed, to give an unidentified substance (40 mg.) with m. p. 168—175°, $[\alpha]_D$ +14° (*c* 1·5), $\nu_{max.}$ (in Nujol) 3257, 1044, 1020, and 966 cm.$^{-1}$, $\lambda_{max.}$ 288 mμ (ε 13,400). Benzene–ether (9 : 1) eluted *ergosta-6,22-diene-3α,5α,8α-triol* (XIII) (210 mg.; m. p.

178—181° after crystallisation from ethyl acetate), $[\alpha]_D$ −23° (*c* 1·7) (Found: C, 78·3; H, 10·9. $C_{28}H_{46}O_3$ requires C, 78·1; H, 10·8%), $\nu_{max.}$ (in Nujol) 3125, 1028, 1012, and 973 cm.$^{-1}$.

Treatment of this triol with acetic anhydride–pyridine at 20° afforded a compound with m. p. 159—161°, $\nu_{max.}$ (in CS_2) 3571, 1751, 1244, 1212, 1014, and 974 cm.$^{-1}$. The molecular extinction coefficient (ε 550) of the acetate peak at 1751 cm.$^{-1}$ showed that only one acetoxyl group was present.

(b) *With zinc and alkali.* A solution of the hydroxy-epidioxide (200 mg.) in 5% methanolic sodium hydroxide (60 ml.) was refluxed with zinc dust (500 mg.) for 1 hr. The mixture was filtered and the filtrate extracted with ether, to give the triol (XIII) (110 mg.), m. p. 175—178°, identified by mixed m. p. and comparison of infrared spectra with an authentic specimen.

(c) *Catalytic reduction.* A solution of the hydroxy-epidioxide (800 mg.) in the minimum volume of ethyl acetate was shaken in hydrogen with prereduced Adams catalyst (70 mg.). *Ergost-22-ene-3α,5α,8α-triol* (III) was precipitated during the hydrogenation, which was stopped after 70 ml. of hydrogen had been adsorbed. After the addition of more ethyl acetate the mixture was warmed to dissolve the triol, and filtered. The filtrate was concentrated and cooled to give the triol (620 mg.) as needles, m. p. 180—203°. Two crystallisations from ethyl acetate afforded material (450 mg.) with m. p. 195—208°, $[\alpha]_D$ −75° (*c* 2·0) (Found: C, 77·8; H, 11·4. $C_{28}H_{48}O_3$ requires C, 77·7; H, 11·2%), $\nu_{max.}$ (in Nujol) 3110, 1030, 1013, and 967 cm.$^{-1}$.

Ergosta-7,22-diene-3α,5α-diol (IV; R = H).—A trace of methanolic hydrochloric acid was added to a solution of the preceding triol (III) (500 mg.) in the minimum volume of methanol. The mixture was shaken at 20° until a precipitate appeared. Water was added and the mixture extracted with ether to give the *diol* (IV; R = H) (250 mg.), m. p. 196—198° (after two crystallisations from ethyl acetate), $[\alpha]_D$ −1° (*c* 1·7) (Found: C, 80·8; H, 11·2. $C_{28}H_{46}O_2$ requires C, 81·1; H, 11·2%), $\nu_{max.}$ (in Nujol) 3115, 1033, 1021, 968, and 864 cm.$^{-1}$. Acetylation at 20° afforded the *acetate* (IV; R = Ac), m. p. 153—155° (plates from methanol), $[\alpha]_D$ −22° (*c* 1·3) (Found: C, 78·5; H, 10·6. $C_{30}H_{48}O_3$ requires C, 78·9; H, 10·6%), $\nu_{max.}$ (in Nujol) 3478, 3430, 1732, 1703, 1258, 1233, 1022, and 967 cm.$^{-1}$.

Ergosta-7,22-dien-3α,5α-ylene Carbonate (XII).—Toluene (75 ml.), saturated with carbonyl chloride at 5°, was added to a solution of the diol (IV; R = H) (150 mg.) in a mixture of pyridine (3 ml.) and chloroform (50 ml.). After being kept at 20° for 2 days the mixture was washed successively with saturated aqueous potassium hydrogen carbonate (to remove excess of reagent), 2N-hydrochloric acid (2 × 50 ml.), aqueous potassium hydrogen carbonate, and water. After evaporation of the dried solution the residue crystallised from acetone, to give the *carbonate* as needles (120 mg.), m. p. 235—239°. Recrystallisation from chloroform–methanol afforded material (80 mg.), m. p. 245—248°, $[\alpha]_D$ 0° (*c* 1·3) [Found: C, 78·7; H, 10·0%; *M* (Rast), 421. $C_{29}H_{44}O_3$ requires C, 79·0; H, 10·1%; *M*, 441], $\nu_{max.}$ (in Nujol) 1718 (C=O; value in CCl_4, 1764), 1252, 1229, 1185, 1078, 1064, and 967 cm.$^{-1}$.

Hydrolysis of the carbonate (35 mg.) with boiling 5% methanolic potassium hydroxide (5 ml.) for 1 hr. gave the 3α,5α-diol (IV; R = H) (20 mg.), m. p. and mixed m. p. 194—196°, $[\alpha]_D$ −1°.

Reduction of 6α-Benzoyloxy-7,22-diene-3β,5α-diol (VII).—Freshly cut lithium (1·05 g.) was added in portions to a stirred solution of the triol monobenzoate [9] (1·5 g.) in ethylamine (125 ml.) containing a few drops of liquid ammonia, the reaction flask being fitted with a " cold finger " filled with acetone and solid carbon dioxide. Stirring was continued for 10 min. after the solution had developed a blue colour: water was then added and the mixture extracted with ether. The material so obtained was dissolved in pyridine (10 ml.) and acetic anhydride (10 ml.) and kept at 20° for 24 hr. The acetylated product was chromatographed on deactivated alumina (150 g.). Light petroleum–benzene (3 : 1) eluted 5α-ergosta-7,22-dien-3β-yl acetate (VIII) (382 mg. after crystallisation from methanol), m. p. and mixed m. p. 182—184°. Elution with benzene (30 ml. portions) gave materials which were collected into two main fractions of about equal weight. The later fraction crystallised from ethyl acetate to give 3β-acetoxy-ergosta-7,22-dien-5α-ol (X) as needles (200 mg.), m. p. and mixed m. p. with authentic material (see below) 227—231°, $[\alpha]_D$ +2° (*c* 1·1).

Ergosta-7,22-diene-3β,5α-diol (IX).[11,12]—A solution of ergosterol epidioxide (V) (1·5 g.) in ether was refluxed with lithium aluminium hydride (1·25 g.) for 2 days. After addition of ethyl acetate and then 2N-sulphuric acid the products were isolated with ethyl acetate and chromatographed on deactivated alumina (100 g.). Benzene–ether (3 : 1) eluted ergosterol (250 mg.), m. p. 156—160° (from methanol). The material eluted with ether crystallised from ethyl

XUM

acetate to give the 3β,5α-diol as plates (583 mg.), m. p. 229—233°, $[\alpha]_D$ +2° (*c* 1·3), $\nu_{max.}$ (in Nujol) 3400, 3284, 1055, 1026, and 975 cm.$^{-1}$. Acetylation with acetic anhydride–pyridine at 20° gave the 3β-acetate (X), m. p. 228—232° (from ethyl acetate), $[\alpha]_D$ +2° (*c* 1·2), $\nu_{max.}$ 3571, 3443, 1735, 1250, and 977 cm.$^{-1}$. Clayton *et al.*[12] found m. p. 227—234°, $[\alpha]_D$ +1° for the diol, and m. p. 228—233°, $[\alpha]_D$ +2° for the monoacetate: Laws's values [11] were m. p. 237—238°, $[\alpha]_D$ +0·5° and m. p. 230—232°, $[\alpha]_D$ 0°, respectively.

5α-Hydroxyergosta-7,22-dien-3-one (XI).—A solution of the 3α,5α-diol (IV; R = H) (95 mg.) in acetone (50 ml.) was cooled by addition of solid carbon dioxide. 8N-Chromic acid (0·2 ml.) was added, and the mixture swirled for 30 sec. and then poured into water. The material isolated with ether was chromatographed on deactivated alumina (10 g.). Benzene eluted the *hydroxy-ketone* (XI) (50 mg.), m. p. 242—244° (from ethanol), $[\alpha]_D$ +5° (*c* 1·6) (Found: C, 81·3; H, 10·65. $C_{28}H_{44}O_2$ requires C, 81·5; H, 10·75%), $\nu_{max.}$ 3400, 1718, 1020, and 965 cm.$^{-1}$.

Oxidation of the 3β,5α-diol (IX) (135 mg.) in acetone (50 ml.) with 8N-chromic acid (0·3 ml.) for 75 sec. at 20° gave the same hydroxy-ketone (75 mg.), m. p. 241—244°.

The authors are indebted to Professor E. R. H. Jones, F.R.S., for his interest and advice, to the Department of Scientific and Industrial Research for a grant (to F. D.), and to Mrs. I. Croxon and Miss D. Trafford for technical assistance.

THE DYSON PERRINS LABORATORY, OXFORD UNIVERSITY. [*Received, November 3rd,* 1960.]

---

365. *The Gaseous Oxidation of Isopropyl Alcohol. Part 1. The Influence of Temperature, Pressure, and Mixture Composition on the Formation of Hydrogen Peroxide and Other Products.*

By A. R. BURGESS, C. F. CULLIS, and E. J. NEWITT.

The gaseous oxidation of isopropyl alcohol can lead to high yields of acetone and hydrogen peroxide. The optimum temperature for the conversion is *ca.* 420° and the yields of the two major products are not substantially affected by pressure. Excess of oxygen has little effect on the yields of peroxides although it enhances the rate of disappearance of acetone. Added acetaldehyde, in contrast to other reaction products, markedly accelerates the reaction.

In the early stages of the oxidation, the only process in operation is a linear chain reaction giving acetone and hydrogen peroxide. However, a small proportion of the initial alcohol is converted into acetaldehyde, further reaction of which is responsible for the onset of autocatalysis; at this stage the yields of the major products start to decrease and considerable amounts of methyl alcohol, formaldehyde, glyoxal, and carbon monoxide are formed.

THE gaseous oxidation of organic compounds at high temperatures generally gives rise, *via* various partially oxidised compounds, to steam and oxides of carbon as final products. Under certain conditions, however, it is possible to isolate certain intermediate oxygenated products in high yield. One such intermediate which is produced during the gaseous oxidation of many aliphatic compounds is hydrogen peroxide, large yields of which are apparently formed from aliphatic alcohols.[1-6] The oxidation of isopropyl alcohol, for example, leads to the production of substantial amounts of hydrogen peroxide and acetone, and a detailed study has recently been made in these laboratories of the gaseous oxidation of this alcohol. In the present paper, the effects of reaction temperature, total pressure,

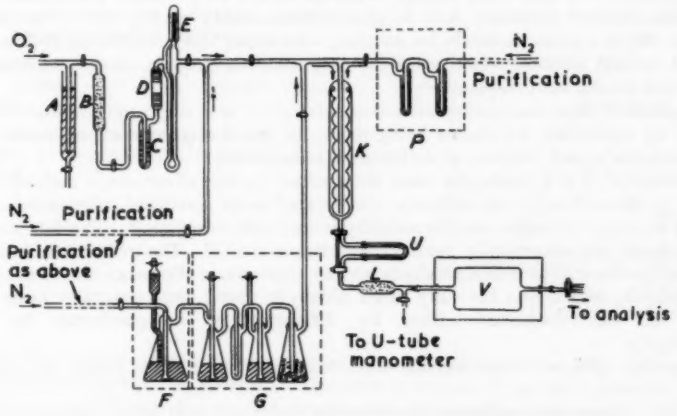
[1] Harris, U.S.P. 2,479,111.
[2] Baccareda and Pedrazzini, *Riv. combustibili,* 1954, **8**, 417.
[3] Cullis and Newitt, *Proc. Roy. Soc.*, 1956, *A*, **237**, 530.
[4] Cullis and Newitt, *Proc. Roy. Soc.*, 1957, *A*, **242**, 516.
[5] Cullis and Newitt, Sixth Symposium on Combustion (London, Butterworth's Scientific Publications, 1957), p. 827.
[6] Cullis and Newitt, *Proc. Roy. Soc.*, 1960, *A*, **257**, 402.

and mixture composition on the products are discussed, and the influence of the surface will be discussed in Part II.

Experimental

Apparatus.—The majority of measurements were made in the flow system, shown diagrammatically in Fig. 1. Oxygen and nitrogen, after being bubbled through a " blow-off " tube, A, were passed through a purification line (B,C,D) followed by a flow-meter, E. Part of the nitrogen stream then flowed through a series of flasks containing isopropyl alcohol at a known temperature. The first of these, F, was kept at a temperature 10° higher than the others, G, and was thus intended to act as a pre-saturator. Nevertheless, even with low gas-flow rates, less than the theoretical quantity of isopropyl alcohol was taken up and the amount passing had therefore to be determined for each set of flow conditions by chemical analysis (see p. 1886). Other additives (*e.g.*, acetone, water) could be introduced into the gas

Fig. 1. *The flow apparatus.*



stream by bubbling another part of the nitrogen through the appropriate liquid contained in traps, P, which were kept at a constant temperature.

The separate streams all entered a gas mixer, K, consisting of three concentric tubes joined at alternate ends and electrically heated to *ca.* 90°, and the mixed gases next passed, *via* a flame trap, L (containing glass chips and glass wool), into the cylindrical Pyrex reaction vessel, V, 12 cm. long and 4·5 cm. in diameter which was enclosed in an electric furnace, the temperature of which was automatically controlled to within ±0·25°.

Most of the runs were at atmospheric pressure. Lower pressures could be maintained by a water-pump connected through a 5-litre reservoir to the outlets of the apparatus. The reactants were mixed and their flow-rates were measured at atmospheric pressure in the usual way. The gases then passed through a small heated capillary restriction, U, into the low-pressure part of the apparatus where the pressure was kept constant by a manostat which opened and closed a small capillary leak in the reservoir.

Some of the experiments on oxidation of acetone were carried out in a static apparatus. This consisted essentially of a cylindrical Pyrex reaction vessel, 8 cm. long and 6·4 cm. in diameter, kept at a constant temperature and connected both to a mercury manometer and to devices for admission of reactants and withdrawal of products. The course of the reaction could be followed both manometrically and by periodic chemical analysis.

Purification of Reactants.—Oxygen and nitrogen. Cylinder gases were purified from carbon dioxide by passage through Sofnolite (B), and dried by concentrated sulphuric acid (C) followed by magnesium perchlorate (D).

Isopropyl alcohol. The alcohol was heated under reflux with stannous chloride to destroy peroxides and with quicklime to remove moisture. It was then fractionally distilled, and the

middle fraction was further purified by distillation from metallic calcium. It was poured into its storage vessel against a stream of pure dry nitrogen; it had b. p. 82·1° (lit., 82·3°).

Acetone. This was purified by the sodium iodide method [7] and then fractionally distilled; it had b. p. 56·2° (lit., 56·2°).

Acetaldehyde. This was freshly distilled in a current of nitrogen and then fractionated *in vacuo*; it had b. p. 21·1° (lit., 21·0°).

Formaldehyde. This was obtained by gentle heating of paraformaldehyde.

Analytical Procedure.—The gases leaving the reaction vessel passed immediately through a series of cold traps in which unchanged isopropyl alcohol and condensable products collected, a partial separation being achieved by having the traps surrounded by different coolants. Permanent gases were analysed qualitatively by an infrared spectrometer, and quantitatively by an Orsat apparatus.

Residual isopropyl alcohol and condensable products were extracted into water and the major constituents of the resulting solutions were determined as follows:

(i) *Alcohols.* The solution was passed through silver oxide to destroy peroxides and to oxidise aldehydes. It was then treated with an excess of standard potassium dichromate solution and sufficient sulphuric acid to give a final acidity of 3% w/v. The solution was heated at *ca.* 95° in a pressure bottle for 40 min., and under these conditions residual isopropyl alcohol and methyl alcohol, which were the only alcohols present, were completely oxidised to acetone and formic acid respectively.[8]

Methyl alcohol alone was estimated colorimetrically [9] and isopropyl alcohol could then be determined by difference, allowance being made for the fact that each molecule of the two alcohols consumes 4 and 2 equiv. of dichromate respectively.

(ii) *Aldehydes.* Total aldehydes were determined by the silver oxide method.[10] For the estimation of formaldehyde the solution was treated with powdered magnesium and hydrochloric acid in order to reduce any formaldehyde–peroxide complex.[11] The formaldehyde was then determined colorimetrically with chromotropic acid.[12] The reduction treatment also converts any formic acid into formaldehyde and an appropriate allowance must be made for this.

Acetaldehyde, which was the only other aldehyde found, was generally present in small quantities. It was estimated either by difference or independently by gas–liquid chromatography.

(iii) *Acetone.* This was determined, after treatment with silver oxide, by the iodoform method.[13]

(iv) *Acids.* These were estimated by titration under nitrogen with a solution of potassium hydroxide in methyl alcohol, phenolphthalein being used as indicator.

(v) *Peroxides.* Hydrogen peroxide, organic peroxides, and peroxy-acids were determined by a modification of the iodometric method.[3]

Minor condensable products (*e.g.*, glyoxal) were identified and estimated by gas–liquid chromatography, using a 12-ft. Embacel column impregnated with polyethylene glycol (M = 400) and a hydrogen flame detector.

Results

(a) *Effect of Temperature.*—The consumption of isopropyl alcohol and the formation of reaction products were determined at temperatures from 350° to 450°. In general, the reaction is preceded by an induction period during which little or no consumption of reactants occurs and at the end of which acetone and peroxides are the first products to appear. The yields of peroxides invariably pass through a maximum with increasing contact time. Below 400°, the yields of acetone, methyl alcohol, and formaldehyde increase continuously with contact time, but above this temperature they also pass through a maximum although this is reached at a somewhat later stage than the peroxide maximum. Some of the analytical results are summarised in Table 1. These show that the optimum temperature for conversion of isopropyl

[7] Shipsey and Werner, *J.*, 1913, **103**, 1255.
[8] Cf. Harris, *Analyst*, 1937, **62**, 729.
[9] Boos, *Analyt. Chem.*, 1948, **20**, 964.
[10] Bailey and Knox, *J.*, 1951, 2741.
[11] Newitt, unpublished results.
[12] Bricker and Johnson, *Analyt. Chem.*, 1945, **17**, 400.
[13] Morgan, Bardwell, and Cullis, *J.*, 1950, 3190.

alcohol into acetone and hydrogen peroxide is *ca.* 420°, and in Fig. 2 are presented the detailed analytical results obtained at this temperature, the yields shown here (and in all subsequent figures) being based on the total amount of isopropyl alcohol passed. Under these conditions 30% of the isopropyl alcohol can be converted more or less completely into acetone and hydrogen peroxide, but the yields of these primary products fall off rapidly if longer contact times are used. The only other products formed in appreciable quantities at this temperature are methyl alcohol, formaldehyde, and glyoxal.

(b) *Effect of Pressure.*—A detailed study of product formation in an equimolar reactant mixture was also carried out at 420° and at a total pressure of 300 mm. Consumption of

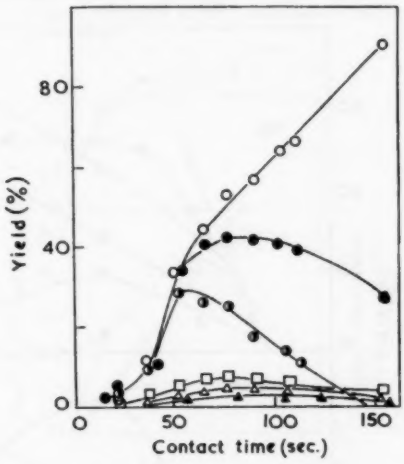


FIG. 2. *Reactant consumption and product formation at atmospheric pressure.*

Temp. 420°; isopropyl alcohol pressure 77·0 mm.; oxygen pressure 81·5 mm.; nitrogen pressure 601·5 mm.

○ Isopropyl alcohol consumed; ● acetone; ◑ total peroxides; □ formaldehyde; △ methyl alcohol; ▲ glyoxal.

isopropyl alcohol and acetone and formation of peroxide are shown in Fig. 3(*a*) alongside the values obtained at atmospheric pressure. Reaction is slower at the lower pressure but roughly the same proportion of isopropyl alcohol consumed is converted into the major products. The peroxide maximum occurs considerably later under reduced pressure conditions and this suggests that such compounds are better preserved at low pressures and that they normally disappear, at any rate, partly by a homogeneous process.

TABLE 1. *Influence of temperature on products formed from reaction of equimolar isopropyl alcohol–oxygen mixtures.*

Temp. (°c)	Induction period (sec.)	Contact time for max. peroxide yield (sec.)	Max. peroxide yield (% of Pr^iOH passed)	Composition of peroxides (% of H_2O_2 in total peroxides)	Yields (% of Pr^iOH passed) of: $COMe_2$	H·CHO	MeOH	Consumption of Pr^iOH
					at time of max. peroxide yield			
350	93	100	4·2	100	7·0	0·25	0·1	7·0
400	35	80	35	66	32	3·1	7·4	47
420	15	55	38	98	35	6·3	3·2	35
450	10	25	32	90	40	10	8·1	60

Formaldehyde, acetaldehyde, and glyoxal are formed in roughly equal amounts in the early stages of reaction [Fig. 3(*b*)] and the yields are similar to those obtained at atmospheric pressure; formaldehyde is, however, subsequently formed in somewhat greater amounts than acetaldehyde. Methyl alcohol first appears at a later stage in the experiments at 300 mm. total pressure but its yield eventually overtakes that found at atmospheric pressure.

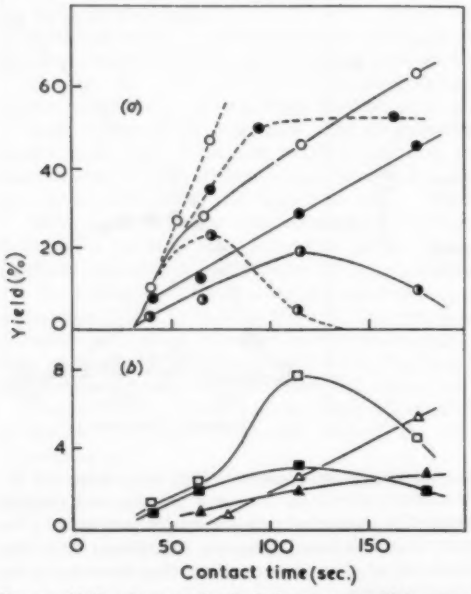
The effect of total pressure on the yields of products at a particular stage of the reaction is shown in Fig. 4. The general pattern of formation of the major products remains largely

XUM

unaffected by total pressure, and the yields are increased at higher pressures although the conversions are little changed. On the other hand, the yields of acetaldehyde remain substantially constant, while methyl alcohol is not formed at all below a pressure of *ca.* 500 mm.

(c) *Effect of Composition of Mixtures.*—Analysis of products was carried out for reactant mixtures containing the same amount of isopropyl alcohol and varying quantities of oxygen, with added nitrogen to make the total flow rate the same in each case. In general, the extents of consumption of isopropyl alcohol and of formation of acetone, peroxides, methyl alcohol, and formaldehyde increase rapidly with oxygen concentration until the oxygen : alcohol ratio

FIG. 3. *Reactant consumption and product formation at reduced pressure.*

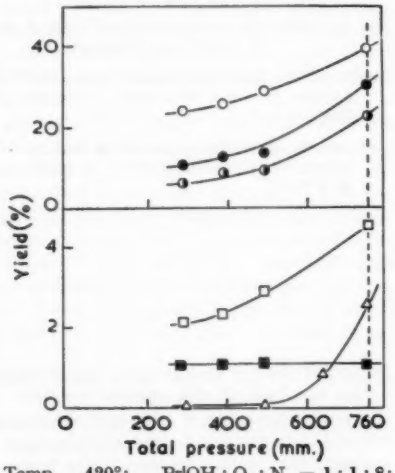


Temp. 420°; isopropyl alcohol pressure 30·0 mm.; oxygen pressure 36·0 mm.; nitrogen pressure 234·0 mm.

Continuous line: reduced pressure. Broken line: atmospheric pressure.

○ Isopropyl alcohol consumed; ● acetone; ◑ total peroxides; □ formaldehyde; ■ acetaldehyde; △ methyl alcohol; ▲ glyoxal.

FIG. 4. *Influence of total pressure on reactant consumption and product formation.*



Temp. 420°; $Pr^iOH : O_2 : N_2 = 1 : 1 : 8$; contact time, 63·5 sec.

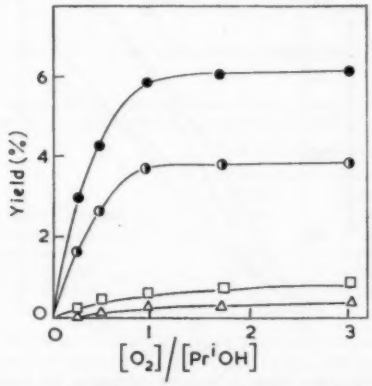
○ Isopropyl alcohol consumed; ● acetone; ◑ total peroxides; □ formaldehyde; ■ acetaldehyde; △ methyl alcohol.

reaches unity. Thereafter the influence of oxygen depends on the stage of the oxidation. Oxygen in excess of that required to give an equimolar mixture has little effect in the early stages of the reaction (Fig. 5). Thus the total isopropyl alcohol consumption remains substantially constant over a large range of oxygen pressures. Acetone and hydrogen peroxide are both formed in considerable yield, and the only difference in oxygen-rich mixtures is the formation of increasing amounts of methyl alcohol and formaldehyde. Oxygen has, however, a much more pronounced effect on the formation of C_1 compounds during the autocatalytic stages of reaction (Fig. 6). In particular, methyl alcohol and carbon oxides do not appear below an oxygen : alcohol ratio of 0·2. Above this value, the yield of carbon monoxide increases linearly with oxygen pressure, and carbon dioxide is not formed until the oxygen : alcohol ratio exceeds 1·3, and then probably only arises from further oxidation of carbon monoxide. Oxygen has little effect on the peroxide yields, which generally reach a maximum during this stage of the reaction. The later stages of oxidation are characterised

by a strong decline in the overall rate of alcohol consumption, rapid decomposition of hydrogen peroxide, and a fall in the yields of acetone. Increase of oxygen pressure enhances the rate of disappearance of both isopropyl alcohol and acetone, but apparently has little effect on the decomposition of hydrogen peroxide or on the formation of aldehydes and methyl alcohol (Fig. 7).

(d) *Effect of Added Products.*—Acetone and formaldehyde have no appreciable effect on the course of the oxidation of isopropyl alcohol. On the other hand, even small additions of acetaldehyde markedly accelerate the reaction (Table 2).

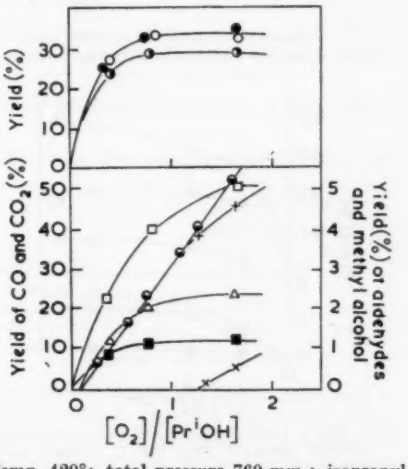
FIG. 5. *Influence of alcohol : oxygen ratio on product formation during early stages of reaction.*



Temp. 420°; total pressure 760 mm.; isopropyl alcohol pressure 46·1 mm.; contact time 21·5 sec.

● Acetone; ◑ total peroxides; □ formaldehyde; △ methyl alcohol.

FIG. 6. *Influence of alcohol : oxygen ratio on product formation during autocatalytic stages of reaction.*



Temp. 420°; total pressure 760 mm.; isopropyl alcohol pressure 65·0 mm.; contact time 51·7 sec.

○ Isopropyl alcohol consumed; ● acetone; ◑ total peroxides; □ formaldehyde; ■ acetaldehyde; △ methyl alcohol; ◒ total carbon oxides; + carbon monoxide; × carbon dioxide.

(e) *Oxidation of Acetone.*—Although acetone is by far the most abundant product of oxidation of isopropyl alcohol, the amounts formed are to some extent reduced by high temperatures and oxygen concentrations, particularly with long contact times. Some further reaction of

TABLE 2. *Influence of added acetaldehyde on the rate of oxidation of isopropyl alcohol.*

Temp. 375°; isopropyl alcohol pressure 50 mm.; oxygen pressure 200 mm.

Pressure (mm.) of added CH_3·CHO	0	0·5	1·0	2·5
Time (min.) for pressure increase of 5 mm.	7·8	5·0	3·9	1·9
Time (min.) for pressure increase of 200 mm.	11·1	9·6	8·4	5·7

acetone evidently occurs under these conditions, and some work was therefore carried out on the gaseous oxidation of acetone itself.

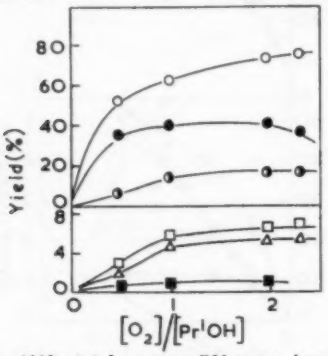
The majority of measurements were made in a static system. Although acetone has been reported to be stable to oxidation below *ca.* 350°,[14] yet mixtures of acetone and oxygen were found to react at temperatures below 300°.[15] An equimolar mixture of acetone and oxygen is

[14] Bardwell, *Proc. Roy. Soc.*, 1951, *A*, **207**, 470.
[15] Avramenko and Neumann, *Acta Physicochim. U.S.S.R.*, 1939, **10**, 601.

XUM

in fact considerably more reactive at 330° than a similar isopropyl alcohol + oxygen mixture (Table 3). The same conclusion emerges from a consideration of the pressure–time curves for oxygen-rich mixtures at 295° (Fig. 8). The initial rate of oxidation at the latter temperature is almost the same as at 375°, but after a pressure rise of *ca.* 10 mm. the rate decreases rapidly at the lower temperature and increases slightly at the higher temperature. Added acetaldehyde increases the initial rate, but after a pressure rise of about six times the initial aldehyde pressure the rate becomes similar to that for the oxidation of acetone alone. Isopropyl

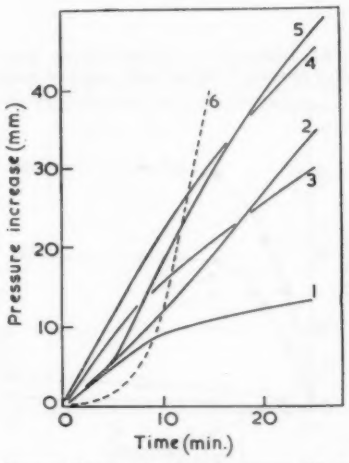
FIG. 7. *Influence of alcohol : oxygen ratio on product formation during late stages of reaction.*



Temp. 420°; total pressure 760 mm.; isopropyl alcohol pressure 76·5 mm.; contact time 106·0 sec.

○ Isopropyl alcohol consumed; ● acetone; ◑ total peroxides; □ formaldehyde; ■ acetaldehyde; △ methyl alcohol.

FIG. 8. *Influence of additives on the oxidation of acetone.*



Continuous lines: Acetone pressure 50 mm.; oxygen pressure 200 mm.

Curve 1, temp. 295°, no additive; curve 2, temp. 375°, no additive; curve 3, temp. 375°, 2·5 mm. of acetaldehyde added; curve 4, temp. 375°, 5·0 mm. of acetaldehyde added; curve 5, temp. 375°, 5·0 mm. of isopropyl alcohol added.

Broken line: Isopropyl alcohol pressure 50 mm.; oxygen pressure 200 mm.
Curve 6, temp. 375°, no additive.

alcohol has no effect until after 6 min. (the induction period normally preceding the oxidation of this compound at 375°), whereupon the rate increases rapidly although it eventually becomes similar to that expected for the oxidation of acetone. However, the fact that the additional

TABLE 3. *Comparison of the oxidation of acetone and isopropyl alcohol.*

Temp. 330°; ketone or alcohol pressure, 100 mm.

Oxygen pressure (mm.)	Induction period (min.)		Max. rate of pressure increase (mm. min.$^{-1}$)		Total pressure increase (mm.)	
	$COMe_2$	Pr^iOH	$COMe_2$	Pr^iOH	$COMe_2$	Pr^iOH
33·5	6·0	—	1·2	—	13	—
49·5	—	15·5	—	1·0	—	38
57·0	2·0	—	4·3	—	28	—
100·0	1·0	13·5	12·2	2·2	55	75

pressure rise is approximately double that accompanying oxidation of isopropyl alcohol alone indicates that the two organic compounds are not reacting completely independently of one another. Analysis of the products at 295° (Table 4) shows that formaldehyde, methyl alcohol,

and glyoxal are all formed although the extent of pressure rise is indicative of some further oxidation of these compounds (*e.g.*, to carbon monoxide).

More detailed analysis was carried out in a flow system at 420° and under these conditions, too, the main product was glyoxal together with methyl alcohol and formaldehyde, and no peroxides could be detected. When acetone was added to an isopropyl alcohol–oxygen mixture

TABLE 4. *Products of the oxidation of acetone.*

Temp. 295°; acetone pressure 50 mm.; oxygen pressure 200 mm.

	Reaction time (min.)	
	7	43
Acetone consumed (mm.)	8·5	16·5
Glyoxal (mm.)	2·5	2·0
Methyl alcohol (mm.)	0·5	1·5
Formaldehyde (mm.)	0·5	0·5
Pressure increase (mm.)	7·5	17·5

TABLE 5. *The influence of addition of acetone on the products of oxidation of isopropyl alcohol.*

Temp. 420°; contact time 111 sec.; oxygen : isopropyl alcohol = 1·13; isopropyl alcohol $8{\cdot}45 \times 10^{-9}$ mole hr.$^{-1}$; additional acetone $3{\cdot}14 \times 10^{-9}$ mole hr.$^{-1}$.

	Flow rate (mole hr.$^{-1}$)			Flow rate (mole hr.$^{-1}$)	
	Acetone not added	Acetone added		Acetone not added	Acetone added
Alcohol consumed	7·28	7·28	Glyoxal	0·38	0·56
Acetone consumed	—	1·14	Peroxides	0·57	0·57
Acetaldehyde	0·04	0·08	Carbon monoxide	6·12	5·06
Formaldehyde	0·36	0·33	Carbon dioxide	0·46	0·40
Methyl alcohol	0·37	0·53			

at the same temperature, appreciable oxidation of the ketone occurred. The consumption of isopropyl alcohol is unchanged in the presence of acetone (Table 5), although the pattern of the formation of products is different. One striking feature is that the decrease in the number of moles of carbon oxides formed is almost exactly equal to the increase in the number of moles of acetone consumed. This suggests that the ketone competes for oxygen with some other compound whose oxidation leads directly to the formation of carbon oxides. The increase in methyl alcohol is similar to that of glyoxal, showing that these products are probably formed together by the oxidation of acetone. There is also a substantial rise in the production of acetaldehyde, which is not normally found among the products of oxidation of acetone.

DISCUSSION

Oxidation of Isopropyl Alcohol.—The first products to be formed during the oxidation of isopropyl alcohol are acetone and hydrogen peroxide. Under optimum conditions for the recovery of hydrogen peroxide about 30% of the initial alcohol is consumed and this appears to react almost entirely according to the overall equation:

$$CHMe_2{\cdot}OH + O_2 = COMe_2 + H_2O_2$$

In general, however, when changes are made to the experimental conditions, the rate of consumption of isopropyl alcohol runs closely parallel with the amounts of acetone and hydrogen peroxide formed. This suggests that attack on the isopropyl alcohol is brought about mainly by HO_2 radicals and that the resulting radicals then react with oxygen to yield acetone, so that oxidation proceeds according to the chain reaction:

$$CHMe_2{\cdot}OH + HO_2 = \dot{C}Me_2{\cdot}OH + H_2O_2$$

$$\dot{C}Me_2{\cdot}OH + O_2 = COMe_2 + HO_2$$

Although this linear chain reaction is effectively the only process in operation during the early stages of the oxidation, other processes also occur in the later stages which do

XUM

not result in the formation of these primary products. The other compounds first to appear are formaldehyde, acetaldehyde, and methyl alcohol, which are probably formed by the thermal decomposition of the radicals derived from isopropyl alcohol:

$$\dot{C}Me_2{\cdot}OH \longrightarrow CH_3{\cdot}CHO + CH_3$$

Acetaldehyde itself readily undergoes further oxidation, and the reaction of methyl radicals with oxygen would be expected to result in the formation of methyl alcohol and formaldehyde (and carbon monoxide).[16-19] In the present system, methyl alcohol is formed at a later stage than formaldehyde, suggesting that the predominant reactions are processes such as:

$$CH_3 + O_2^- \longrightarrow H{\cdot}CHO + OH$$

Alternatively, if methoxy-radicals are formed as a result of the reactions [16]

$$CH_3 + O_2 \longrightarrow CH_3{\cdot}O_2{\cdot}$$
$$2CH_3{\cdot}O_2{\cdot} \longrightarrow 2CH_3{\cdot}O{\cdot} + O_2$$

they appear to be further oxidised rather than to stabilise themselves by abstraction of hydrogen. Since little or no carbon monoxide can be detected at this stage, alkoxy-radicals probably react with oxygen to yield an aldehyde and an HO_2 radical: [20]

$$CH_3{\cdot}O{\cdot} + O_2 \longrightarrow H{\cdot}CHO + HO_2{\cdot}$$

The products which are present at the beginning of the autocatalytic stage and might be responsible for chain-branching are acetone, hydrogen peroxide, formaldehyde, and acetaldehyde.

Now, when the surface conditions are unfavourable for the preservation of hydrogen peroxide, the overall rate of reaction decreases, but the time of onset of the autocatalytic stage is unaffected. Thus it seems unlikely that this compound is responsible for chain branching. Similarly experiments on addition of acetone and formaldehyde prove conclusively that neither of these compounds is capable of starting a branching reaction. On the other hand, introduction of small quantities of acetaldehyde decreases, or even eliminates, the induction period so it is probably this compound which is responsible for chain branching in the present system. If the formation (or further oxidation) of acetaldehyde could be prevented, the linear chain cycle would continue more or less unaffected, resulting in the exclusive formation of acetone and hydrogen peroxide.

Oxidation of Acetone.—Even below 400°, appreciable further oxidation of acetone evidently occurs. The main products are glyoxal, methyl alcohol, and formaldehyde. The appearance of these C_1 and C_2 products at such an early stage, and the absence of peroxides, makes it unlikely that initial attack involves simple abstraction of hydrogen from the ketone molecule. On the other hand, early C–C bond fission appears to be involved. The chain reaction occurring at much lower temperatures involves formation of formaldehyde, methyl alcohol, and possibly methylglyoxal,[21] but glyoxal itself has not previously been reported among the products of oxidation of acetone.

Since the only plausible mode of initial attack involving C–C bond fission and production of free radicals would be:

$$CH_3{\cdot}CO{\cdot}CH_3 + O_2 = CH_3{\cdot}CO + CH_3{\cdot}O_2{\cdot}$$

---

[16] Raley, Porter, Rust, and Vaughan, *J. Amer. Chem. Soc.*, 1951, **73**, 15.
[17] Hentz, *J. Amer. Chem. Soc.*, 1953, **75**, 5810.
[18] Taylor and Blacet, *Ind. Eng. Chem.*, 1956, **48**, 1505.
[19] Ingold and Bryce, *J. Chem. Phys.*, 1956, **24**, 360.
[20] Jolley, *J. Amer. Chem. Soc.*, 1957, **79**, 1537.
[21] Christie, *J. Amer. Chem. Soc.*, 1954, **76**, 1979.

and since there is abundant evidence that the only fate of acetyl radicals at the temperatures concerned is decomposition according to the reaction:[22-24]

$$CH_3{\cdot}CO{\cdot} = CH_3{\cdot} + CO$$

it seems that the reaction occurring may be a molecular rather than a radical process. Such a conclusion would be consistent with the absence of any specific effect of added acetone on the rate of oxidation of isopropyl alcohol. On the other hand, the possibility of acetone's undergoing a radical-induced oxidation is shown by the enhanced consumption of ketone which is found in an isopropyl alcohol–oxygen mixture.

The authors thank Laporte Chemicals Ltd. for the provision of a Research Studentship for one of them (A. R. B.) and for valuable financial assistance in the purchase of apparatus.

CHEMISTRY DEPARTMENT, IMPERIAL COLLEGE, LONDON, S.W.7. [*Received, July 20th,* 1960.]

[22] Pitts and Blacet, *J. Amer. Chem. Soc.*, 1952, **74**, 455.
[23] Grumer, Fifth Symposium on Combustion (New York: Reinhold Publishing Corporation, 1955), p. 447.
[24] Blanchard, Farmer, and Ouellet, *Canad. J. Chem.*, 1957, **35**, 115.

---

366. *The Reaction of Diboron Tetrachloride with Ethylene Oxide.*

By A. G. MASSEY and A. K. HOLLIDAY.

Diboron tetrachloride reacts rapidly with ethylene oxide at −78° to form the liquid tetra-(2-chloroethoxy)diboron, which reacts slowly with oxygen and trimethylamine. Cold aqueous hydrolysis gives 2-chloroethanol and sub-boric acid; hydrolysis by strong alkalis at 90° breaks the boron–boron bond to give hydrogen. Pyrolysis up to 135° produces tri-(2-chloroethoxy)-boron; and at 240° causes complete decomposition to ethylene, dioxan, 1,2-dichloroethane, and ethyl chloride.

ETHYLENE OXIDE might be expected to form stable co-ordination complexes with tervalent boron compounds, *e.g.*, $R_3\bar{B}-\overset{+}{O}(CH_2)_2$. However, Edwards, Gerrard, and Lappert [1] have shown that excess of ethylene oxide reacted with boron trichloride at −78° to form tri-(2-chloroethoxy)boron:

$$BCl_3 + 3(CH_2)_2O \longrightarrow B(O{\cdot}CH_2{\cdot}CH_2Cl)_3$$

In this work diboron tetrachloride reacted rapidly with more than 4 moles of ethylene oxide at −78° to give a viscous liquid. Freezing the product in liquid nitrogen produced a glass which had no definite melting point; increasing the temperature slowly decreased the viscosity until at 100° the liquid was quite mobile. There were no volatile products, and alkaline hydrolysis of the residue produced up to 90% of the hydrogen expected if there was no fission of the boron–boron bonds. The probable product of the reaction is therefore tetra-(2-chloroethoxy)diboron:

$$B_2Cl_4 + 4(CH_2)_2O \longrightarrow B_2(O{\cdot}CH_2{\cdot}CH_2Cl)_4$$

As in all reactions of diboron tetrachloride, some decomposition to boron trichloride occurred, accounting for the incomplete recovery of hydrogen on hydrolysis. Moreover, polymerisation of ethylene oxide is readily initiated by boron trichloride [1] and by other boron compounds,[2] and the ethylene oxide used in excess of the 4 moles required was therefore probably polymerised. Presence of this polymer may account for the viscous nature

[1] Edwards, Gerrard, and Lappert, *J.*, 1957, 348.
[2] Worsfold and Eastham, *J. Amer. Chem. Soc.*, 1957, **79**, 901.

of the product, since compounds analogous to tetra-(2-chloroethoxy)diboron, *e.g.*, tetramethoxydiboron [3] and tri-(2-chloroethoxy)boron [4] are not viscous liquids at ordinary temperatures.

Separation of pure tetra-(2-chloroethoxy)diboron from the polymeric contaminant could not be achieved, but hydrolysis gave further evidence of its presence as 80—90% of the reaction product. Hydrolysis by cold water gave 2-chloroethanol as the only volatile product, with only a trace of hydrogen and hydrochloric acid, indicating the reaction

$$B_2(O{\cdot}CH_2{\cdot}CH_2Cl)_4 + 4H_2O \longrightarrow 4CH_2Cl{\cdot}CH_2{\cdot}OH + B_2(OH)_4$$

and confirming the virtual absence of boron–chlorine bonds. The solution had strong reducing properties, as expected for sub-boric acid; the latter gave boric acid and hydrogen when hydrolysed with alkali. Prolonged alkaline hydrolysis was necessary to release chloride ion from the original product.

When mixed with oxygen, the product did not inflame even when heated. A slow reaction occurred; B–B bonding disappeared after 22 hr. at ordinary temperature, and 0·5 mole of oxygen was used for each mole of diboron tetrachloride reacting. The products were white boric oxide and an involatile liquid shown by infrared and nuclear magnetic resonance spectra to be tri-(2-chloroethoxy)boron. The reaction is therefore similar to that of oxygen and diboron tetrachloride,[5] *viz.*,

$$6B_2(O{\cdot}CH_2{\cdot}CH_2Cl)_4 + 3O_2 \longrightarrow 2B_2O_3 + 8B(O{\cdot}CH_2{\cdot}CH_2Cl)_3$$

and a similar mechanism [6] involving initial co-ordination of an oxygen molecule across the B–B bond may well operate.

Tetra-(2-chloroethoxy)diboron reacted very slowly with trimethylamine at room temperature or above, but not to the extent required for donation to both boron atoms. The reaction was so slow that some thermal decomposition inevitably proceeded to a considerable extent, making any interpretation of the results difficult. Tri-(2-chloroethoxy)boron also reacted very slowly with trimethylamine to form a similar white solid adduct.

Tetra-(2-chloroethoxy)diboron had greater thermal stability than diboron tetrachloride. The only major indication of decomposition at moderate temperatures was the slow disappearance of the boron–boron bonds; thus a 22% loss occurred after 6 days at 20°, or a 71% loss after 22 hr. at 135°. The infrared spectrum of the involatile liquid residue indicated the presence in it of tri-(2-chloroethoxy)boron; the only volatile products were traces of dioxan and 1,2-dichloroethane. However, at 240° the decomposition was rapid and accompanied by extensive charring, and the evolution of ethylene, dioxan, ethyl chloride, and 1,2-dichloroethane; the residues from pyrolyses at 240° gave no ionisable chlorine on hydrolysis with distilled water at room temperature. This indicated that no boron–chlorine bonds had re-formed during the decomposition; however, some boron–carbon bonds were obviously present in the residues because the boron was not all titratable as boric acid after alkaline hydrolysis. The absence of any solid products of pyrolysis below 135° precludes the possibility of the type of disproportionation previously suggested for diboron tetra-alkoxides,[7] *viz.*,

$$3B_2(O{\cdot}CH_2{\cdot}CH_2Cl)_4 \longrightarrow 2B + 4B(O{\cdot}CH_2{\cdot}CH_2Cl)_3$$

A more probable mechanism is analogous to that obtained in the case of diboron tetrachloride: [3]

$$nB_2Cl_4 \longrightarrow nBCl_3 + (BCl)_n$$

$$nB_2(O{\cdot}CH_2{\cdot}CH_2Cl)_4 \longrightarrow nB(O{\cdot}CH_2{\cdot}CH_2Cl)_3 + (CH_2Cl{\cdot}CH_2{\cdot}OB)_n \quad (I)$$

[3] Schlesinger, Wartik, Moore, and Urry, *J. Amer. Chem. Soc.*, 1954, **76**, 5293.
[4] Jones, Thomas, Pritchard, and Bowden, *J.*, 1946, 824.
[5] Apple and Wartik, *J. Amer. Chem. Soc.*, 1958, **80**, 6153.
[6] Holliday and Massey, *J. Inorg. Nuclear Chem.*, 1961, in the press.
[7] Wiberg and Ruschmann, *Ber.*, 1937, **70**, 1393.

A chloroethylboroxole (I; $n = 3$) would contain boron–carbon as well as boron–oxygen bonds.

The slow reactions of tetra-(2-chloroethoxy)diboron with oxygen and trimethylamine are to be expected if, as in $B(OR)_3$ compounds, there is a considerable degree of double bonding between the boron and oxygen atoms, with the consequent filling of the vacant boron orbitals, which would cause a reduction in the acceptor powers of the boron atoms. It is of interest that this also enhanced the stability of tetra-(2-chloroethoxy)diboron with respect to disproportionation, thus supporting the hypothesis [8] that the instability of B_2X_4 compounds is due, not to an inherent weakness of the boron–boron bond, but to a tendency to internal co-ordination with subsequent rupture of the boron–boron bond.

Experimental

The preparation of diboron tetrachloride has been described previously.[9] Ethylene oxide was purified by passage through a trap held at −78°; the material volatile at −78° was distilled at reduced pressure, and the middle fraction retained: v. p. at 0°, 494 mm.

Reaction of Diboron Tetrachloride with Ethylene Oxide.—The results are summarised in Table 1; quantities are expressed in mmoles unless otherwise stated. In Experiment 1, reaction was vigorous at −78° to give a colourless liquid; no change was noted on warming the system to 40° when the excess of ethylene oxide was removed. Hydrolysis here was with concentrated sodium hydroxide solution at 90° for 2 hr.

In expt. 2, low acidity and hydrogen values were obtained after hydrolysis with a large excess of distilled water at 0° for 1 hr.; this produced an oil. The acidity of the hydrolysate slowly rose to 0·07 mequiv. after 12 hr. The boric acid was estimated only after addition of concentrated alkali and boiling, followed by acidification.

In expt. 3, hydrolysis was again controlled, 3·66 mmoles of water being used at 20° for 1 hr.

Table 1.

Expt. No.	1	2	3
B_2Cl_4 used	0·71	0·81	0·89
C_2H_4O added	4·90	4·48	4·95
C_2H_4O recovered	1·54	0·93	0·59
Reaction temp.	−78° to 40°	−78° to 22°	−78°
Hydrolysis products:			
H_2	0·64	0·01	0·74
Cl^-	2·88	—	—
$B(OH)_3$	1·38	1·62	—
H^+	—	0·03	—

Table 2.

Expt. No.	4	5	6	7	8	9
B_2Cl_4 used	0·79	0·71	0·81	0·75	0·84	0·79
C_2H_4O used	3·57	3·49	3·81	3·60	3·78	3·44
Decomposition temp.	22°	40°	90°	135°	240°	240°
Time of decomposition, hr.	144	0·5	21	22	19	44
Volatile products: H_2	—	—	—	—	0·03	0·02
CH_4	—	—	—	—	—	trace
C_2H_6	—	—	—	—	0·01	0·01
C_2H_4	—	—	—	—	0·03	0·25
X	—	—	0·01	0·03	0·23	0·23
Hydrogen on hydrolysis of residue	0·62	0·64	0·55	0·22	0·00	—
% recovery of B–B bond	78	90	69	29	0	—

The small amount of oily product was distilled off and identified as 2-chloroethanol by its infrared spectrum and by its reaction with potassium hydroxide, which gave water and ethylene oxide. The hydrogen was obtained after further hydrolysis of the solid residue by strong alkali.

Decomposition of the reaction product. The experiments are summarised in Table 2. In

[8] Feeney, Holliday, and Marsden, *J.*, 1961, 356.
[9] Holliday and Massey, *J.*, 1960, 43.

XUM

expts. 4 and 5 there were no volatile products. Fraction X in expt. 6 was pure dioxan, and in 7, fraction X contained a trace of 1,2-dichloroethane in addition to dioxan. Considerable charring of the product was noted in expts. 8 and 9; fraction X now contained relatively large amounts of dioxan, 1,2-dichloroethane, and ethyl chloride. The residue in expt. 8 was hydrolysed with concentrated caustic alkali at 90° but no hydrogen was produced; titration of the hydrolysate gave chloride 2·83, and boric acid 1·41 mequivs.: B : Cl = 1 : 2·01. In expt. 9, the residue was hydrolysed with a large excess of distilled water; no hydrogen and very little acidity (0·01 mequiv.) could be detected.

Reaction product–oxygen reactions. Diboron tetrachloride (0·79) and ethylene oxide (4·65) were held at −78° for 30 min.; 1·22 mmoles of oxide were recovered. 1·30 mmoles of pure, dry oxygen were added to the product at −196°; warming cautiously to −78° produced no apparent reaction. On warming to 22° there still appeared to be no reaction; after 22 hr. at 22°, 0·90 mmole of oxygen was removed: ratio $O_2 : B_2Cl_4 = 0{\cdot}40 : 0{\cdot}79$. No hydrogen was evolved on hydrolysis of the colourless residue by concentrated alkali. Other mixtures of oxygen and the reaction product failed to ignite when brought rapidly to room temperature (or above) from −196° (cf. the reaction of diboron tetrachloride with oxygen [5]). Boric oxide was apparent in the reaction vessels as a faint white precipitate. The involatile liquid product gave the infrared and nuclear magnetic resonance spectra of $B(O{\cdot}CH_2{\cdot}CH_2Cl)_3$.

Reaction product–trimethylamine reactions. Diboron tetrachloride (0·78 mmole) reacted with ethylene oxide (3·42 mmoles) at −78°. Trimethylamine (2·12) was added to the product and the vessel kept at 22° for 1 hr. A small quantity of white solid was produced and 0·37 mmole of amine was absorbed; after 2 days at 22°, 1·43 mmoles of amine were recovered; amine reacted = 0·69 mmole. Alkaline hydrolysis of the residue (a mixture of liquid and solid) produced 0·65 mmole of hydrogen. Similar reactions with tri-(2-chloroethoxy)boron showed that trimethylamine was again slowly absorbed but not in stoicheiometric quantities.

We thank the Department of Scientific and Industrial Research for a maintenance grant (to A. G. M.), and Dr. L. H. Sutcliffe, who carried out the proton magnetic resonance studies.

Department of Inorganic and Physical Chemistry,
The University of Liverpool. [*Received, July 25th,* 1960.]

---

367. *Structural Correlations in the Nuclear Magnetic Resonance Spectra of Bisbenzylisoquinoline and Aporphine Alkaloids.*

By I. R. C. Bick, J. Harley-Mason, N. Sheppard, and M. J. Vernengo.

The hydrogen nuclear magnetic resonance spectra of a range of bisbenzylisoquinoline alkaloids, and of a few aporphine alkaloids, have revealed a number of useful correlations between the resonance positions of methoxyl and *N*-methyl groups and the chemical and stereochemical structures of these molecules. These correlations have been used to make predictions about the structures of the incompletely characterised alkaloids tenuipine, nortenuipine, and chondrofoline.

We have examined the hydrogen (proton) nuclear magnetic resonance spectra of several series of alkaloids, mostly of the bisbenzylisoquinoline type, and have found that some useful correlations may be made between the chemical shifts of certain functional groups and their structural and stereochemical locations. The stereochemical variations within this class of alkaloid are of considerable complexity, owing to the presence of two asymmetric centres adjacent to the nitrogen atoms, and to the possible relative locations of the two ether linkages. The correlations recorded here are mostly concerned with the strong and sharp methyl resonances of the methoxyl and methylimino-groups, but a few other regularities are also recorded. The data so obtained have been of assistance in assigning structures to three incompletely characterised alkaloids.

XUM

Goodwin, Shoolery, and Johnson,[1] on the basis of experimental data from three aporphine alkaloids, previously suggested that the resonances of methoxyl and aromatic CH groups might give rise to useful correlations in the alkaloid field.

EXPERIMENTAL.—Except where otherwise specified, the substances concerned were examined in approximately saturated solutions in chloroform. The chemical shifts are quoted in parts per million on the τ scale[2,3] relative to the resonance of tetramethylsilane as an internal standard at $\tau = +10{\cdot}00$. The measurements were made at 40 Mc. sec.$^{-1}$ with a Varian Associates 12″ electromagnet, and a V-4300 B spectrometer, with tubes of 5 mm. outside diameter, sample spinning, and flux stabilisation. Calibration of the peaks was made by using side bands generated by a Muirhead-Wigan D 695 A decade oscillator. During the early part of this work the positions of the peaks were measured relative to the solvent (chloroform) resonance and these have been calculated to the τ scale by assuming $\tau = +2{\cdot}75$ for chloroform. Subsequent measurements were made directly against tetramethylsilane used as an internal standard in the chloroform solutions. As the latter values are likely to be somewhat more accurate the names of the appropriate compounds are indicated by asterisks in Tables 1—3. Errors due to the earlier procedure are unlikely to exceed $\pm 0{\cdot}05$.

DISCUSSION

Resonances of OMe *and* NMe *Groups.*—(a) *Factors affecting the chemical shifts of such groups.* A methoxyl group attached to a benzene ring has a normal chemical shift of *ca.* 6·2 on the τ scale (anisole in chloroform gives 6·17). This chemical shift is an average value taken over the various orientations of the methoxyl group with respect to the benzene ring reached by rotation about the aromatic C–O bond. Benzene rings are magnetically very anisotropic because applied magnetic fields readily generate currents in the π-electron system.[4] The sense of this anisotropy is such that the hydrogen nuclei of a methoxyl group lying in the plane of the ring will have a somewhat lower chemical shift than those of a methoxyl group above or below the ring, *i.e.*, lying so that the plane of the C–O–C atoms is perpendicular to that of the ring.[4,5] The presence of bulky substituents near such a group will tend to force it out of the aromatic plane, *i.e.*, to favour higher τ values by a few hundredths of a unit. More pronounced shifts to higher τ values by several tenths of a unit are found when a methoxyl group can take up configurations so that its hydrogen atoms fall more directly over the top of a second adjacent benzene ring.[5,6] This is the predominant cause of the marked spread of methoxyl resonances (6·05—6·98) observed with these alkaloids. The methylimino-resonances also exhibit a range of values (7·35—7·75) for the same reasons.

(b) *The repandine–oxyacanthine* (I) *and berbamine–tetrandrine* (II) *series.* Table 1 summarises chemical shift data for a number of alkaloids of each of these two series, and for the related compound cepharanthine (III). In addition to the strong and sharp resonances of methoxyl and methylimino-groups, we also list the position of the maxima of the broader collective resonances of the ring methylene groups. Some typical spectra are shown in Fig. 1. Many of the chemical-shift regularities shown in Table 1 speak for themselves; we shall only point out the salient features.

Methoxyl groups at position 4″ have a chemical shift (6·05—6·13) that is slightly lower than the normal value of ~6·2, whereas the same group at position 7 has a very high value (6·80—6·98). An examination of molecular models showed that the 7-methoxy-group can, and in many of its orientations must, pass closely over the top of the adjacent aromatic ring B; this is certainly the cause of the high chemical shift. The purely

[1] Goodwin, Shoolery, and Johnson, *Proc. Chem. Soc.*, 1958, 306.
[2] Tiers, *J. Phys. Chem.*, 1958, **62**, 1151.
[3] Jackman, "Applications of Nuclear Magnetic Resonance in Organic Chemistry," Pergamon Press, London, 1959.
[4] Bernstein, Schneider, and Pople, *Proc. Roy. Soc.*, 1956, *A*, **236**, 515.
[5] Bovey and Johnson, *J. Chem. Phys.*, 1958, **29**, 1012.
[6] Fessenden and Waugh, *J. Amer. Chem. Soc.*, 1957, **79**, 846.

XUM

empirical evidence does not allow a clear-cut assignment of the chemical shifts at *ca.* 6·25 and 6·35—6·7 to methoxyl groups at positions 6 and 6′. However, the series of peaks of lower chemical shift have been provisionally assigned to 6-methoxyl on the grounds that

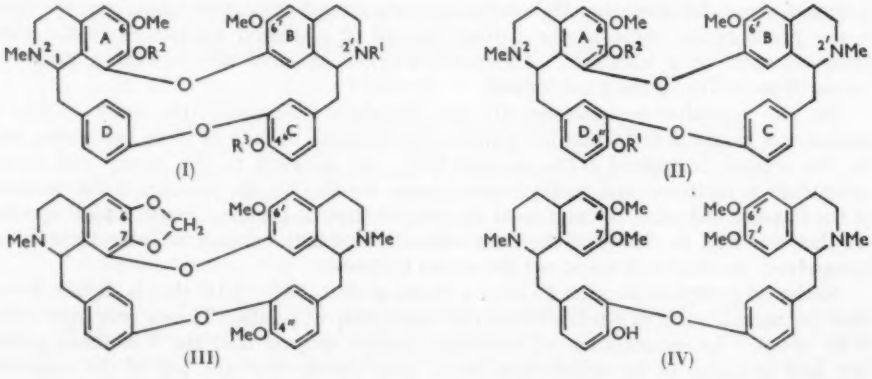
TABLE 1. *Chemical shift data* (τ *values*) *for alkaloids of the repandine–oxyacanthine–berbamine–tetrandrine–pheanthine series.*‡

Name	Formula	R¹	R²	R³	OMe 4″	OMe 6	OMe 6′	OMe 7	Ring CH_2	NMe 2′	NMe 2
Repandine	I(++)	Me	Me	H	—	6·27	6·62	6·98	7·20	7·50	7·50
O-Methylrepandine	I(++)	Me	Me	Me	6·05	6·25	6·60	6·95	7·22	7·45	7·45
Oxyacanthine *	I(+−)	Me	Me	H	—	6·27	6·44	6·85	7·12	7·52	7·52
O-Methyloxyacanthine *	I(+−)	Me	Me	Me	6·10	6·21	6·40	6·80	7·05	7·35	7·45
Daphnandrine	I(+−)	H	H	Me	6·12	6·25	6·40	—	7·12	—	7·50
Aromoline §	I(+−)	Me	H	H	—	6·23	6·44	—	—	7·51	7·51
Daphnoline †	I(+−)	H	H	H	—	6·17	6·35	—	—	—	+
Cepharanthine	III(+−)	—	—	—	6·10	—	6·30	—	7·05	7·35	7·42
Berbamine *	II(−+)	H	Me	—	—	6·18	6·35	6·85	7·1	7·35	7·75
Isotetrandrine *	II(−+)	Me	Me	—	6·05	6·22	6·37	6·82	7·07	7·40	7·72
Tetrandrine	II(++)	Me	Me	—	6·10	6·27	6·65	6·82	7·00	7·41	7·70
Fangchinoline	II(++)	Me	H	—	6·03	6·23	6·60	—	6·94	7·38	7·62
Pheanthine *	II(−−)	Me	Me	—	6·13	6·28	6·68	6·80	6·92	7·40	7·70
Pycnamine *	II(−−)	H	Me	—	—	6·27	6·82	6·82	—	7·37	7·65

* Data for these molecules are somewhat more accurate (see Experimental section). § Weak spectrum owing to limited solubility in chloroform. † Solution in formic acid; weak spectrum. ‡ Chemical evidence for the structures of most of these alkaloids is summarised by Kulka, "The Alkaloids," ed. Manske and Holmes, Academic Press, New York, Vol. IV, p. 199, and Vol. VII, p. 439; the structures of daphnandrine, aromoline, and daphnoline have been reported by Bick, Clezy, and Vernengo (*J.*, 1960, 4928) and that of pycnamine by von Bruchhausen *et al.* (personal communication; *Arch. Pharm.*, 1960, **293**, 785).

the group at position 6′ occupies a position more closely analogous to that of 7. Molecular models confirm that the 6′-methoxyl group approaches the top of the aromatic ring A.

A potentially very useful regularity is that when the asymmetric carbon centres are paired (+−) or (−+) the 6′-methoxyl resonance, as assigned above, has a chemical shift



near 6·4, whereas the pairing (++) or (−−) gives a value near 6·65. Models show that in the latter case the methyl-hydrogen atoms are less free to move away from the adjacent aromatic ring. The 6′-methoxyl resonance of cepharanthine has an abnormally low value.

For alkaloids of the repandine type both methylimino-resonances occur near 7·45, whereas for the berbamine series they give well separated peaks near 7·4 and 7·7. Monobenzylisoquinoline alkaloids normally have their methylimino-resonances between 7·45

and 7·5 (Table 3). However molecular models show that the *N*-methyl group at position 2 in the alkaloids in the berbamine series approaches the top of aromatic ring D, and therefore we have assigned the *ca.* 7·7 chemical shift to the methylimino-group at this position.

Dauricine (IV) has a simpler spectrum than those discussed above, as would be expected from the fact that the two tetrahydroisoquinoline rings are no longer joined by an ether bridge. There are two methoxy-resonances at 6·20 and 6·45, each of which corresponds to two groups, probably at positions 6 and 6′ and 7 and 7′ respectively. As there is no ether

FIG. 1. *Nuclear magnetic resonance spectra of*: 1, *repandine*; 2, *O-methyloxyacanthine*; 3, *isotetrandrine*; 4, *tetrandrine*; 5, *pheanthine*.

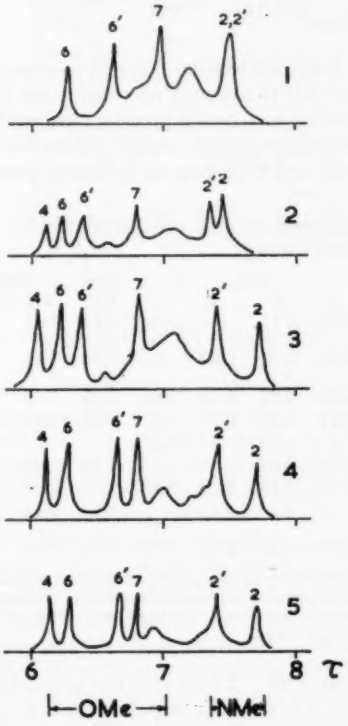
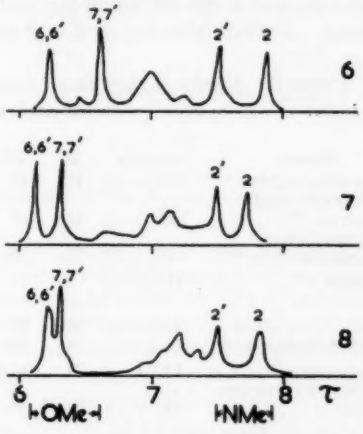


FIG. 2. *Nuclear magnetic resonance spectra of*: 6, *OO′-dimethylisochondrodendrine*; 7, *OO′-dimethylcurine*; 8, *OO′-dimethylchondrocurine*.

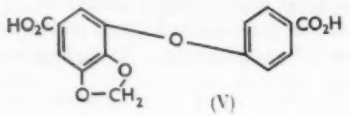


bridge to cause the 7-methoxy-group to be held close to an adjacent aromatic ring the chemical shift value has returned much closer to the normal value although its resonance is still separate and distinguishable from that of the 6-methoxyl groups, presumably because of the effect of the adjacent benzyl aromatic ring. The methylimino-peaks overlap at 7·50 and the broad ring CH_2 resonance occurs at 7·23.

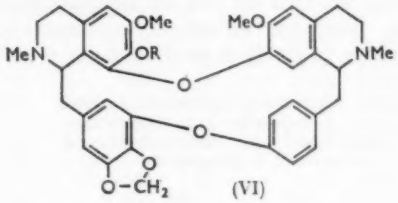
The correlations set out above have been used to make tentative structural assignments for the incompletely characterised alkaloids tenuipine and nortenuipine (previously described as de-*N*-methyltenuipine [7]). The former compound has methoxyl peaks at 6·25, 6·65, and 6·82, a pair of methylimino-peaks at 7·40 and 7·65, and a peak at 4·02 to be attributed to the methylenedioxy-group. The three methoxy-resonances may clearly be

[7] Bick, Taylor, and Todd, *J.*, 1953, 695.

assigned to positions 6, 6′, and 7 respectively (see Table 1), and the absence of a peak near 6·1 suggests that there is no methoxyl attached to the benzyl residue. This has been confirmed by the isolation of repandulinic acid (V) by oxidation,[8] and thus position 4 is taken up by one end of the methylenedioxy-ring as in (VI; R = Me). The presence of



(V)



(VI)

two *N*-methyl peaks indicates that the alkaloid is of the berbamine–tetrandrine type, and the high value of the 6′-resonance suggests that the pair of asymmetric centres are (++) or (−−). The nuclear magnetic resonance evidence has hence greatly narrowed the structural possibilities for tenuipine, and degradations are being carried out to test this evidence. Nortenuipine has methoxyl peaks at 6·22 and 6·67, two methylimino-peaks at

TABLE 2. *Chemical shift data (τ values) for alkaloids of the isochondrodendrine–curine and chondrocurine series.*‡

Name	Formula	R¹	R²	R³	OMe 6	OMe 6′	OMe 7	OMe 7′	Ring CH_2	NMe 2′§	NMe 2§
Isochondrodendrine *	VII(−−)	H	H	—	6·13	6·13	—	—	7·12	7·47	7·73
O-Methylisochondrodendrine †*	VII(−−)	Me	H	—	6·23	6·23	6·59	—	7·02	7·51	7·65
OO′-Dimethylisochondrodendrine *	VII(−−)	Me	Me	—	6·22	6·22	6·62	6·62	7·00	7·50	7·87
Insularine *	VIII(−−)	—	—	—	6·18	6·25	6·70	—	6·99	7·46	7·52
					6	6′	7	4″			
Curine	IX(−−)	Me	H	H	6·07	6·07	—	—	7·12	7·53	7·70
OO′-Dimethylcurine *	IX(−−)	Me	Me	Me	6·12	6·12	6·32	6·32	7·12	7·48	7·70
Chondrocurine *	IX(+−)	H	Me	H	—	6·12	6·18	—	7·10	7·55	7·75
OO′-Dimethylchondrocurine	IX(+−)	Me	Me	Me	6·20	6·20	6·30	6·30	7·20	7·50	7·82

* Chemical shift data for these compounds are slightly more accurate (see experimental section). † Very weak spectrum. ‡ Chemical evidence for the structures of these alkaloids is summarised by Wintersteiner in "Curare and Curare-like Agents," Elsevier," Amsterdam, 1959, p. 153. § Assigned tentatively on the basis of molecular models (see text).

7·37 and 7·68, and a broad ring CH_2 resonance at 7·00. These and the properties of nortenuipine indicate that 7-methoxyl is replaced by a hydroxyl group, but that otherwise the structure is closely related to that of tenuipine, *i.e.*, (VI; R = H).

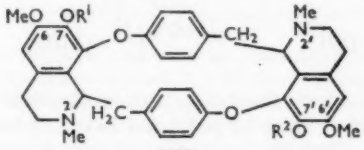
(c) *The* Curare *series.* In these series of bisbenzylisoquinoline alkaloids the two halves of the molecule are joined by head-to-tail linkages instead of the head-to-head, tail-to-tail links of the alkaloids discussed in Section (b). Molecules of the isochondrodendrine series are the more symmetrical, but even in isochondrodendrine itself (VII; $R^1 = R^2 = H$) the molecule as a whole lacks a centre of symmetry because of the (−−) configurations at the two asymmetric centres. Insularine (VIII) is closely related to this series. Curine (IX; $R^1 = Me$, $R^2 = R^3 = H$) and chondrocurine (IX; $R^2 = Me$, $R^1 = R^3 = H$) differ from the isochondrodendrine series in the location of one of the ether bridges.

The nuclear magnetic resonance data for these compounds are collected in Table 2 and some typical spectra are shown in Fig. 2.

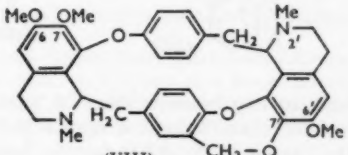
[8] Bick, Doebel, Taylor, and Todd, *J.*, 1953, 692, and unpublished results.

Considering first the methoxyl resonances we see that for all these compounds the 6- or 6′-substituents give rise to relatively normal chemical shifts (6·07—6·25). The somewhat higher values for 6′-methoxyl as observed in the repandine–berbamine series no longer occur, because the more extended structures of these molecules do not bring the 6′-methoxy-group in close proximity to an adjacent benzene ring. The 7,7′-methoxy-groups in the isochondrodendrine series have somewhat higher values (~6·65), but in the curine–chondrocurine series they too are only slightly higher than normal (6·18—6·32).

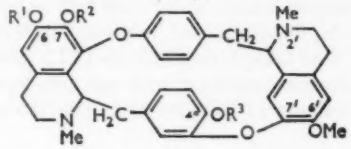
Table 2 also shows that all the compounds of the two main series have one normal *N*-Me resonance at ~7·5 and a higher peak at 7·75. Insularine (VIII) is an exception to



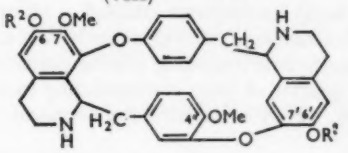
(VII)



(VIII)



(IX)



(X)

this generalisation but its structure is more rigid because of the formation of the additional ring.

Molecular models for these classes of alkaloid show considerably more flexibility than for the repandine–berbamine classes, and for this reason detailed interpretations are more difficult here. In all cases molecular conformations can be found which can account for the regularities in the spectral data of Table 2, but it is not immediately obvious why these conformations are more probable than others which would be expected to give different results. Conversely, the spectroscopic data may be of use in the future in providing evidence for the most probable conformations of these molecules. However, it does appear from the models that for chondrocurine a high value of a methylimino-resonance is likely to go with a low 7-methoxyl value on the same ring and therefore in Table 2 we tentatively assign the higher *N*-Me resonance to position 2.

Chondrofoline is an alkaloid of the curine group whose detailed structure is uncertain although King [9] has provisionally formulated it as (X; R^1 = Me or H, and *vice-versa* for R^2) on the basis of degradations and colour reactions. However, the spectrum clearly shows the presence of two methylimino-groups (7·47 and 7·71) and this confirms more recent analytical results.[10] Further, the three methoxyl groups give a pair of resonances close to 6·15 and one at 6·26, suggesting that both R^1 and R^2 may be methyl groups and that the hydroxyl group may be at position 7 or 4″. However, this does not accord with King's location of the hydroxyl group from the Millon test; further work may enable a decision to be made between these possible structures, but in the meantime it may be noted that fangchinoline,[11] an alkaloid of the tetrandrine series, responds exceptionally to the test.

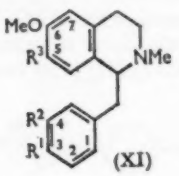
(d) *Some benzylisoquinoline and aporphine alkaloids.* In Table 3 we compare chemical shift data for several examples of each of these two classes of alkaloid.

[9] King, *J.*, 1940, 737; cf. Bick and Clezy, *J.*, 1960, 2404.
[10] Bick, unpublished results.
[11] Hsing Chi-Yi and Chang Ching-Hsiang, *Acta Chim. Sinica*, 1957, **23**, 405.

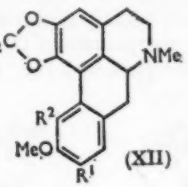
XUM

Results for dicentrine, *O*-methylbulbocapnine, and glaucine have been published recently by Goodwin, Shoolery, and Johnson;[1] their results, when approximately converted to the present units, agree with ours to within less than 0·1 τ unit. The data on isocorydine methochloride are taken from a paper by Katritzky, Jones, and Bhatnagar.[12]

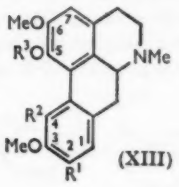
It is seen that for both classes of alkaloid the chemical shifts of methoxyl groups



(XI)



(XII)



(XIII)

adjacent to two benzene rings at positions 5 have consistently higher chemical shifts (6·37—6·58) than those at 2, 3, or 6 (6·11—6·28). Those at position 4 have intermediate chemical shifts (6·28—6·35) for the aporphine alkaloids; only one example is available for a benzylisoquinoline alkaloid. All methylimino-resonances lie between 7·45 and 7·65.

Resonances of Methylenedioxy-groups.—Goodwin, Shoolery, and Johnson [1] showed that the methylenedioxy-ring joining positions 5 and 6 of aporphine alkaloids (XII) gives rise to a quartet of lines corresponding to a small chemical shift between the two hydrogen atoms. They attributed the chemical non-equivalence of the two hydrogen atoms to a

TABLE 3. *Chemical shift data* (τ *values*) *for alkaloids of the benzylisoquinoline and aporphine series.* ‡

Name	Formula			OCH₃					NCH₃	OCH₂O
	R¹	R²	R³	2Δ	3Δ	4	5	6Δ		
±) -Laudanosine	XI	OMe	OMe	OMe	—	6·18	6·22	6·45	6·18	7·48	—
O-Methylarmepavine ...	XI	OMe	H	OMe	—	6·20	—	6·58	6·28	7·45	—
(+)-*O*-Ethyl-*N*-methyl-coclaurine	XI	OH	H	OEt	—	—	—	—	6·20	7·48	—
Dicentrine *	XII	OMe	H	—	6·20	6·20	—	—	—	7·62	4·05, 4·20 (doublets)
Bulbocapnine *	XII	H	OH	—	—	6·20	—	—	—	7·65	3·97, 4·15 (doublets)
O-Methylbulbocapnine	XII	H	OMe	—	—	6·18	6·28	—	—	7·50	3·95, 4·15 (doublets)
Corydine *	XIII	H	OMe	H	—	6·18	6·35	—	6·18	7·55	—
O-Methylcorydine *	XIII	H	OMe	Me	—	6·18	6·32	6·37	6·18	7·50	—
Glaucine *	XIII	OMe	H	Me	6·20	6·25	—	6·45	6·20	7·57	—
Isocorydine metho-chloride §	XIII	H	OH	Me	—	6·11	—	6·46	6·16	—	—

* These data are somewhat more accurate (see experimental section). ‡ Chemical evidence for the structures of these alkaloids is summarised by Manske in "The Alkaloids," ed. Manske and Holmes, Academic Press, New York, Vol. IV, p. 119 and Vol. VII, p. 423. § Data from ref. 12. Δ Assignments of resonance to these positions may be interchanged.

non-planarity of the linked biphenyl ring system. Sasaki [13] has made a particular study of the resonances of methylenedioxy-groups attached to benzene rings (including some alkaloids), and his data, when recalculated into our units with the help of his values for cepharanthine and isotetrandrine, show that such groups usually have their resonance between 3·7 and 4·6. This accords with our values of 4·42, 4·02, and 4·00 for cepharanthine, tenuipine, and nortenuipine respectively, and with the values listed in Table 3 for the dicentrine-type alkaloids. In agreement with the ideas expressed by Goodwin *et al.*[1] the resonances are single except for those from aporphine alkaloids, although in the case of cepharanthine the line is broad, suggesing incipient splitting caused by a small chemical shift between the two methylenedioxy-hydrogen atoms.

Aromatic CH *Resonances.*—Goodwin, Shoolery, and Johnson [1] have pointed out that

[12] Katritzky, Jones, and Bhatnagar, *J.*, 1960, 1950.
[13] Sasaki, *J. Pharm. Soc. Japan*, 1960, **80**, 241.

the pattern of lines caused by aromatic CH groups of the aporphine alkaloids can often be used effectively to check the positions of substituents around the benzene rings. Although we have also made use of such data in a number of simple cases, we have not yet attempted a detailed analysis of this region of the spectrum for the present compounds, partly because chloroform as a solvent somewhat obscures the resonances, and partly because the four benzene rings of the bisbenzylisoquinoline alkaloids give overlapping, and therefore complex spectra. Nevertheless, some interesting regularities have been observed in the overall patterns of bands in this region; for example, the two curine spectra are similar in appearance but differ from those of the chondrocurines, while chondrofoline has a similar spectrum to that of the curines. We hope that a further study of this region of the spectrum will give more detailed information on a number of points of structure and conformation.

We gratefully acknowledge the award of Research Grants from the Consejo Nacional de Investigaciones Científicas y Técnicas of Argentina (to M. J. V.), and of a Royal Society and Nuffield Foundation Commonwealth Bursary (to I. R. C. B.). Generous gifts of material were received from Professor Masao Tomita (cepharanthine, insularine, and *O*-methylarmepavine); Professor F. von Bruchhausen (pycnamine); Dr. J. D. Dutcher (curine, chondrocurine, and isochondrodendrine); Dr. J. Walker (chondrofoline); Dr. J. R. Price (pheanthine); Dr. J. A. D. Jeffries (*O*-ethyl-*N*-methylcoclaurine); Dr. R. H. F. Manske (glaucine and dauricine); Dr. T. Kikuchi (*O*-methylisochondrodendrine); and Professor S. Kupchan (fangchinoline).

University Chemical Laboratory,
Lensfield Road, Cambridge.

[*Received, August 22nd,* 1960.]

---

368. *The Nucleotide Sequence in Deoxyribonucleic Acids. Part V.* The Alkaline Degradation of Apurinic Acids.*

By C. R. Bayley, K. W. Brammer, and A. S. Jones.

Degradation of apurinic acids in N-potassium hydroxide at 37° or at pH 12 at 56° gave, in addition to oligonucleotides, an αβ-unsaturated aldehyde phosphate (probably II), the formation of which can be explained if the degradation proceeded by a β-elimination. The amount of this product indicated that about 45% of the degradation proceeded by this mechanism. Over 20% of the apurinic acid phosphorus was converted into inorganic phosphate, probably by simultaneous or consecutive cyclisation and β-elimination.

Apurinic acids (I), the products of the mild acid hydrolysis of deoxyribonucleic acids,[1] are degraded by alkali.[2] As all the interpyrimidine nucleotide linkages remain intact, examination of the degradation products should give information on the distribution of pyrimidines in deoxyribonucleic acids.[2] Two types of mechanism have been suggested for this alkaline degradation, (*a*) cyclisation,[2] which could be either at positions 3′, 4′ or at positions 4′, 5′, and (*b*) β-elimination.[3]

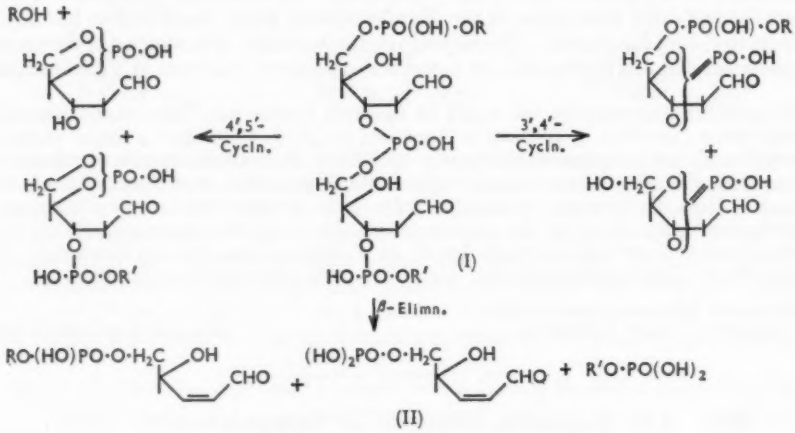
We have now obtained definite evidence that part of the degradation takes place by β-elimination. Thus apurinic acid was much more unstable than ribonucleic acid at pH 10 and 37°, so that they are probably degraded by different mechanisms, and ribonucleic acid is known to break down by cyclisation.[4] Paper chromatography of the products formed by degradation of apurinic acid with N-potassium hydroxide at 37° revealed, in addition to oligonucleotides, a component which appeared as a red spot with aniline hydrogen

* Part IV, *J.*, 1957, 2454.

[1] Tamm, Hodes, and Chargaff, *J. Biol. Chem.*, 1952, **195**, 49.
[2] Tamm, Shapiro, Lipshitz, and Chargaff, *J. Biol. Chem.*, 1953, **203**, 673.
[3] Brown and Todd, "Nucleic Acids," Vol. I, Academic Press, New York, 1955, p. 444.
[4] Brown and Todd, *J.*, 1952, 52.

XUM

phthalate and gave a positive reaction for phosphate.[5] In distilled water the product had $\lambda_{max.}$ 249 mμ and gave an immediate red colour with Schiff's reagent.[6] The ultraviolet absorption spectrum differed from those of the purines, pyrimidines, and their nucleosides and nucleotides, found in deoxyribonucleic acids, particularly by the absence of the peak or shoulder at 270—280 mμ which is present in the spectra of guanine derivatives. These properties indicated that the component was probably the αβ-unsaturated aldehyde



R and R′ = chain of pyrimidine nucleotide units.

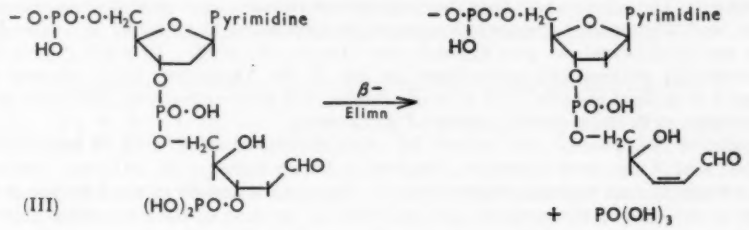
phosphate (II) which would be expected to arise by β-elimination. On the assumption that the substance contained 1 atom of phosphorus per molecule, $\epsilon_{max.}$ was 8000, which is within the range quoted for αβ-unsaturated carbonyl compounds.[7] Woodward[8] found that αβ-unsaturated ketones usually have $\lambda_{max.}$ 225 ± 5 mμ; Evans and Gillam[7] showed that αβ-unsaturated aldehydes have $\lambda_{max.}$ 208—245 mμ, depending on the degree of substitution, increasing substitution generally increasing $\lambda_{max.}$. The even higher $\lambda_{max.}$ of this component can be attributed to substitution by both a hydroxyl and a CH_2·O·PO(OH)$_2$ group. Further evidence was that the substance formed a 2,4-dinitrophenylhydrazone whose $\lambda_{max.}$ (384 mμ) was characteristic of 2,4-dinitrophenylhydrazones of αβ-unsaturated aldehydes.[9]

The amount of αβ-unsaturated aldehyde phosphate (II) (measured by means of its phosphorus content [1]) produced in N-potassium hydroxide at 37° rose to a maximum of 6·3% after 14 hr. and then slowly decreased (to 1·1% after 356 hr.). The decrease may have been due to oxidation, hydrolysis, elimination of phosphate, reaction with other compounds in the alkaline solution, or tautomeric change. (αβ-Unsaturated carbonyl compounds in some cases, readily isomerise to βγ-tautomers in alkali.[10]) The present appears to be a particularly favourable case as further tautomerism to 5-hydroxylævulaldehyde 5-phosphate would ensue: the latter has, however, not been detected. Extrapolation of the results to zero decomposition showed that 6·5—7·5% of the apurinic acid phosphorus had been converted into " αβ-unsaturated aldehyde phosphorus." Similar

[5] Hanes and Isherwood, *Nature*, 1949, **164**, 1107.
[6] Tobie, *Ind. Eng. Chem. Analyt.*, 1942, **14**, 405.
[7] Evans and Gillam, *J.*, 1943, 565.
[8] Woodward, *J. Amer. Chem. Soc.*, 1941, **63**, 1123.
[9] Roberts and Green, *J. Amer. Chem. Soc.*, 1946, **68**, 218.
[10] Ingold, " Structure and Mechanism in Organic Chemistry," Bell, London, 1953, p. 562.

results were obtained when apurinic acid was treated at pH 12 at 56°, but decomposition of the αβ-unsaturated aldehyde phosphate was very slight.

Compound (II) would arise by β-elimination only from those sites in the original deoxyribonucleic acid where at least two purine nucleotides were adjacent, so that if all the degradation proceeded by this mechanism the amount of compound (II) should be the same as the amount of inorganic phosphorus produced by the degradation of apurinic acid or deoxyribonucleic acid with diphenylamine and formic acid as described by Burton.[11] The apurinic acid used in this work gave 16·5% of inorganic phosphorus when degraded under these conditions. This was much lower than that obtained by Burton (25%) for



the degradation of herring testes deoxyribonucleic acid,[12] the difference arising because our apurinic acid was prepared by prolonged acid-hydrolysis of commercial herring-sperm deoxyribonucleic acid and was therefore considerably degraded. It contained 0·31 mol. of purines, 2·79 mol. of pyrimidines, and only 0·90 mol. of non-glycosidically bound 2-deoxy-D-ribose per 4 g.-atom of phosphorus. It can be concluded, therefore, that a maximum of 45% of the alkaline degradation of apurinic acid proceeds by a β-elimination.

During the alkaline degradation, 20—26% of the apurinic acid phosphorus was converted into inorganic phosphate. A small proportion of this could have arisen from the hydrolysis or elimination of phosphate from the αβ-unsaturated aldehyde phosphate (II). The remainder could arise by almost simultaneous rupture of both 3′- and 5′-phosphate linkages, as may occur during the Burton degradation;[11] however, this cannot account for all of the inorganic phosphate produced, and it seems more probable that compounds such as (III) are formed by a cyclisation degradation mechanism and that these then eliminate phosphate as shown.

The occurrence of two types of degradation also presents the possibility that the αβ-unsaturated aldehyde phosphate (II), or an isomer of it, arises as the result of a secondary reaction by elimination of phosphate from a compound formed by a cyclisation mechanism.

The alkaline degradation of apurinic acid is obviously very complex, so it is to be expected that for a given pyrimidine sequence many oligonucleotide fragments would result. The complexity of the decomposition has been somewhat reduced by the formation of dithioacetals of apurinic acid,[13] but even in this case it has been found[14] that calf-thymus apurinic acid di(carboxymethyl) dithioacetal gives over 70 components on alkaline degradation owing to the formation of several products for a given nucleotide sequence. The degradation of apurinic acid and deoxyribonucleic acid by Burton's method,[11] in which diphenylamine and formic acid are used, appears to give only one product for each sequence of pyrimidine nucleotides and as yet appears to cause little fission of inter-pyrimidine nucleotide linkages.

[11] Burton, *Biochem. J.*, 1956, **62**, 315; Burton and Peterson, *ibid.*, 1960, **75**, 17.
[12] Burton, *Biochem. J.*, 1960, **75**, 35P.
[13] Jones and Letham, *J.*, 1956, 2573; Jones, Letham, and Stacey, *J.*, 1956, 2579, 2584; Jones, Stacey, and Watson, *J.*, 1957, 2454; Kent, Lucy, and Ward, *Biochem. J.*, 1955, **61**, 529.
[14] Cunningham and Jones, unpublished results.

XUM

Experimental

Analytical Methods.—Nitrogen was determined by Ma and Zuazaga's method,[15] total phosphorus as described by Jones, Lee, and Peacocke,[16] and inorganic phosphorus by Berenblum and Chain's procedure.[17] Base analyses were carried out by Wyatt's method.[18]

Apurinic Acids.—(a) *Calf thymus.* This was prepared from highly polymerised calf-thymus deoxyribonucleic acid by the method described by Tamm *et al.*[1] The product contained 0·13 mole of guanine, 0·07 mole of adenine, 0·87 mole of cytosine, and 1·14 moles of thymine per 4 g.-atoms of phosphorus. (b) *Herring sperm.* Commercial herring-sperm deoxyribonucleic acid (3 g.; Isaac Spencer & Co.; more than half of the cytosine in this material had been degraded to uracil) was dissolved in 0·025N-hydrochloric acid (800 ml.) and set aside at 37° for 48 hr. The solution was then dialysed against running tap-water at room temperature for 24 hr. and then against frequent changes of distilled water at 0° for 48 hr. The dialysed solution was freeze-dried, to give apurinic acid (1·8 g.; N, 7·4%; P, 8·35%). Analysis of this material for purines and pyrimidines (by Mr. T. W. Thompson, B.Sc.) showed that it contained 0·16 mole of guanine, 0·15 mole of adenine, 0·61 mole of cytosine, 0·73 mole of uracil, and 1·45 moles of thymine per 4 g.-atoms of phosphorus.

Degradation of Apurinic Acid at pH 10.—Calf-thymus apurinic acid (4 mg.) and yeast ribonucleic acid (4 mg.) were separately dissolved in borate buffer of pH 10 (2 ml.) and dialysed at 37° for 36 hr. against the same buffer (20 ml.). The optical density of the diffusate at 260 mμ was 0·84 in the case of the apurinic acid and 0·50 in the case of the ribonucleic acid. This showed that 40% of the apurinic acid hydrolysate and 12% of the ribonucleic acid hydrolysate had diffused through the membrane. A similar experiment was carried out on herring-sperm apurinic acid in carbonate buffer of pH 10 for 3 days at 37°. 43% of the material (as measured by phosphorus analysis) diffused through the membrane. When herring-sperm nucleic acid was dissolved in distilled water and dialysed against distilled water at 37°, 7% of the phosphorus diffused through the dialysis membrane.

Degradation of Apurinic Acid with N-*Potassium Hydroxide.*—Herring-sperm apurinic acid (500 mg.) was dissolved in N-potassium hydroxide (90 ml.) and set aside at 37° for 18 hr. The solution was neutralised with perchloric acid, potassium perchlorate filtered off, and the filtrate concentrated *in vacuo* to 30 ml. Chromatography of this solution (5 ml.) on Whatman No. 3 paper in propan-2-ol–ammonia (*d* 0·880)–water (70 : 6 : 30) gave a component of R_P 0·10 which absorbed ultraviolet light ($\lambda_{max.}$ 249 mμ), gave a brown spot with a silver nitrate spray,[19] a red spot with aniline hydrogen phthalate,[20] and a blue spot with the Hanes and Isherwood[5] phosphate-detecting spray. Several other components were present. These had lower R_P values, had $\lambda_{max.}$ at about 265 mμ and gave positive reactions with silver nitrate and phosphate-detecting sprays, but gave no reaction with aniline hydrogen phthalate.

The component of R_P 0·10 was eluted from several sheets of paper, and the eluate (200 ml.) concentrated *in vacuo* to 20 ml. The solution gave an immediate colour with sensitive Schiff's reagent.[6] Phosphorus analyses showed that the eluate contained about 4% of the phosphorus of the apurinic acid. On the assumption that the compound contained 1 atom of phosphorus per mol. the $\varepsilon_{max.}$ was 8000. Appropriate paper controls were taken for all these determinations.

A portion of the eluate (3 ml.) and a similar eluate of blank paper were concentrated *in vacuo* to 0·5 ml. and added to a boiling methanol solution (5 ml.) of 2,4-dinitrophenylhydrazine (15 mg.) containing 1 drop of 10N-hydrochloric acid. The solutions were cooled and then examined by paper chromatography on Whatman No. 1 paper. With butan-1-ol–ethanol–ammonia (*d* 0·880)–water (40 : 10 : 1 : 49) as solvent, three components of R_P 0·00, 0·76, and 0·86 were obtained in the test solution. The component of R_P 0·86 was 2,4-dinitrophenylhydrazine and that of R_P 0·76 was also present in the solution from the eluate of blank paper. The component remaining on the origin when eluted with water had $\lambda_{max.}$ 384 mμ. The reaction mixture was also chromatographed in water saturated in butan-1-ol, a component of R_P 0·75

[15] Ma and Zuazaga, *Ind. Eng. Chem. Analyt.*, 1942, **14**, 280.
[16] Jones, Lee, and Peacocke, *J.*, 1951, 623.
[17] Berenblum and Chain, *Biochem. J.*, 1938, **32**, 295.
[18] Wyatt, *Biochem. J.*, 1951, **48**, 584.
[19] Trevelyan, Procter, and Harrison, *Nature*, 1950, **166**, 444.
[20] Partridge, *Nature*, 1949, **164**, 443.

and a streak extending from the origin to R_F 0·5 being obtained. The former had $\lambda_{max.}$ 384 mμ and the latter was mainly due to 2,4-dinitrophenylhydrazine.

Rate of Formation of the αβ-Unsaturated Aldehyde Phosphate (II).—(*a*) Herring-sperm apurinic acid (500 mg.) was dissolved in N-potassium hydroxide (100 ml.) and set aside at 37°. At intervals, samples (5 ml.) were removed and neutralised with perchloric acid, potassium perchlorate was filtered off, and the filtrate concentrated *in vacuo* and submitted to paper chromatography for 2 days on Whatman No. 3 paper with propan-2-ol–ammonia (*d* 0·880)–water (70 : 1 : 30). The αβ-unsaturated aldehyde phosphate was located by spraying with aniline hydrogen phthalate a strip cut from the chromatogram, and the required zone was cut out and eluted with distilled water at 37° for 18 hr. The ultraviolet absorption spectra and phosphorus contents were measured. Control determinations were carried out on strips cut from blank areas of the paper. The ultraviolet absorption spectra of all the samples had $\lambda_{max.}$ 249 mμ. The results of the phosphorus analyses were as tabulated.

Amount (%) *of apurinic acid* P *converted into αβ-unsaturated aldehyde* P.

Time (hr.)	1·5	4	6·5	11	12	13	14	15	16	17	18	37·5	44·5	61·5	86	133	158	188	230	356
Amount (%)	3·0	4·1	5·1	5·9	5·9	6·0	6·3	6·3	6·2	6·1	6·3	4·3	4·3	3·4	2·9	2·0	2·0	1·6	1·4	1·1

After 356 hr. at 37°, 21·4% of the apurinic acid phosphorus had been converted into inorganic phosphate.

(*b*) Herring-sperm apurinic acid (250 mg.) was dissolved in 0·01N-potassium hydroxide (200 ml.) and set aside at 56°. During the first 24 hr., N-potassium hydroxide was added at intervals to maintain the pH at 12. Samples (5 ml.) were withdrawn and the " αβ unsaturated aldehyde phosphorus " determined as described above. The results were as follows:

Time (hr.)	3·5	23	46·5	95	125	168	264
Amount (%) converted	4·1	6·4	6·4	5·7	5·7	6·0	6·0

After 23 and 168 hr., 9·7% and 25·8% respectively of the apurinic acid phosphorus had been converted into inorganic phosphate.

Treatment of Apurinic Acid with Diphenylamine and Formic Acid.[11]—Herring-sperm apurinic acid (10 mg.) and highly polymerised herring-sperm deoxyribonucleic acid (10 mg.) were separately dissolved in 66·7% formic acid (6 ml.) containing 2% of diphenylamine and set aside at 29° for 19 hr. The inorganic and total phosphorus contents of the solutions were then determined. 26·3% of phosphorus of the deoxyribonucleic acid and 16·5% of that of the apurinic acid were converted into inorganic phosphate.

The authors thank Professor M. Stacey, F.R.S., for his interest, the Medical Research Council for a Research Grant (to C. R. B.), and Monsanto Chemicals Ltd. for a Research Scholarship (to K. W. B.).

CHEMISTRY DEPARTMENT, THE UNIVERSITY,
EDGBASTON, BIRMINGHAM, 15.

[*Received, September 16th*, 1960.]

XUM

369. *Synthesis of* NN-*Dialkyl*-N′-*arylalkyl*-N′-4-*quinazolyl*(or 6-*methyl*-4-*pyrimidyl or* 4-*methyl*-2-*pyrimidyl*)*ethylenediamines of Potential Pharmacological Interest.*

By N. B. Chapman and H. Taylor.

A series of compounds of the types mentioned in the title, with methyl or ethyl as alkyl groups, and benzyl or 4-substituted benzyl as arylalkyl group, has been synthesised by condensing the appropriate chloro-heterocyclic compound with a *NN*-dialkyl-*N*′-arylalkylethylenediamine. These tertiary-secondary bases have been prepared by reduction with triethylamine formate of the anils obtained by condensation of *NN*-dimethyl- or *NN*-diethyl-ethylenediamine with benzaldehyde or *para*-substituted benzaldehydes.

The ultraviolet absorption spectra of *N*′-benzyl-*NN*-dimethylethylenediamine, of 4-benzylaminoquinazoline, and of *N*-benzyl-*N*′*N*′-dimethyl-*N*-4-quinazolylethylenediamine revealed that ditertiary amines of the type prepared undergo protonation in aqueous media first at the nitrogen atom bearing the alkyl groups, and secondly at a ring-nitrogen atom.

pK_a values of the conjugate acids so formed have been measured and the influence of molecular structure on these values is discussed. The pharmacological properties of the compounds are briefly noted and discussed.

Hetramine (*N*-benzyl-*N*′*N*′-dimethyl-*N*-2-pyrimidyl-) and Neohetramine or Thonzylamine (*N*-4-methoxybenzyl-*N*′*N*′-dimethyl-*N*-2-pyrimidyl-ethylenediamine) are well-known histamine antagonists. We therefore thought it of interest to synthesise for pharmacological evaluation two series of analogous compounds: one containing a 6-methyl-4-pyrimidyl group and the other a 2-methyl-4-pyrimidyl group in place of the 2-pyrimidyl group in the above structures, and with a range of substituents in the 4-position of the benzyl group (fluorine, chlorine, bromine, methyl, and methoxyl). As preliminary observations had shown that analogous 4-quinazolyl derivatives had analeptic properties, a group of quinazoline derivatives was also included.

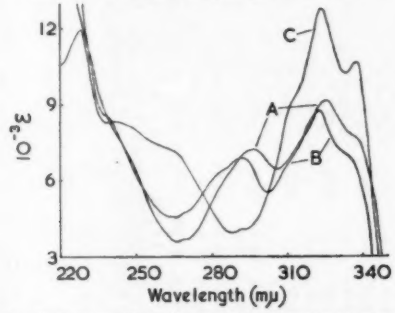
Condensation of the appropriate chloro-heterocyclic compound with a *NN*-dialkyl-*N*′-arylalkylethylenediamine under conditions detailed in the Experimental section gave, sometimes in indifferent yield, the required ditertiary amines as viscous, high-boiling oils which did not give good analyses. They were therefore characterised through analytically pure derivatives, usually picrates, and by determination of equivalent weight titrimetrically, both of the redistilled base and of the picrate. The required secondary-tertiary amines were obtained by reduction of anils obtained from benzaldehyde or a 4-substituted benzaldehyde and *NN*-dialkylethylenediamines, a method based on the work of Villani and his co-workers.[1] The anils were successfully reduced with triethylamine formate, excess of formic acid and the consequent acidic conditions being avoided. After initial experiments with a representative pure anil, it was found unnecessary to isolate the anil, so that this part of the synthesis could be achieved in virtually one stage. The necessary primary-tertiary amines were obtained by minor modifications of published methods.[2] Substituted benzaldehydes not available commercially were prepared by Beech's method,[3] *viz.*, formation of the oxime by interaction of a diazonium salt with formaldoxime and subsequent hydrolysis.

Although 4-chloroquinazoline reacted smoothly with *N*′-benzyl-*NN*-dimethylethylenediamine in boiling nitromethane to give the hydrochloride of the required product, it was found more suitable to condense the chloro-compound with the other secondary-tertiary amines without a solvent at 120—130°. Attempts to recrystallise hydrochlorides of the

[1] Villani, Sperber, Long, and Papa, *J. Amer. Chem. Soc.*, 1950, **72**, 2724.
[2] Bloom, Breslow, and Hauser, *J. Amer. Chem. Soc.*, 1945, **67**, 539.
[3] Beech, *J.*, 1954, 1297.

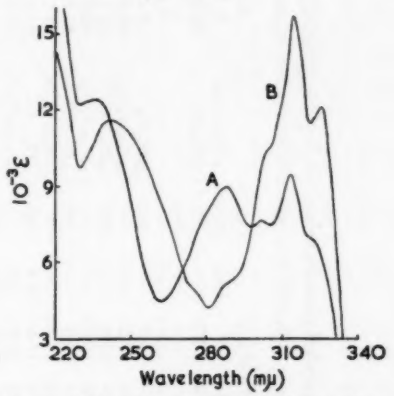
quinazoline derivatives from aqueous media led to fission of the molecule and isolation of the hydrochlorides of the corresponding secondary-tertiary amines with loss of the 4-quinazolyl group. Direct condensation of the chloropyrimidines with secondary-tertiary amines at 120—130° gave poor yields (20%) and much decomposition, and although reducing the temperature to 70—80° gave better yields (30%), decomposition, causing difficulties in purification, was still encountered. It was found best to condense the base and 4-chloro-6-methylpyrimidine in aqueous suspension, since despite extensive side reactions, the main products could readily be purified and the consumption of the chloro-compound could be followed by titration of the chloride ion formed. Aqueous acetic acid was found to be a more satisfactory medium for the analogous condensations of 4-chloro-2-methylpyrimidine. Often bases with the *NN*-dimethyl group consumed

FIG. 1. *Absorption spectra of* N-*benzyl*-N'N'-*dimethyl*-N-4-*quinazolylethylenediamine.*



A, *In* 0·1N-*sodium hydroxide.* B, *At* pH 6·8. C, *In* 0·1N-*hydrochloric acid.*

FIG. 2. *Absorption spectra of* 4-*benzylamino-quinazoline.*



A, *In* 0·1N-*sodium hydroxide.* B, *In* 0·1N-*hydrochloric acid.*

chloro-compound more rapidly than those with the *NN*-diethyl group, but from the latter better yields were obtained.

The ultraviolet absorption spectra of *N'*-benzyl-*NN*-dimethylethylenediamine, of 4-benzylaminoquinazoline (Fig. 2), and of *N*-benzyl-*N'N'*-dimethyl-*N*-4-quinazolylethylenediamine (Fig. 1) have been determined. The pK_a values for the two most stable conjugate acids formed by each of the ditertiary amines prepared were also measured by a method detailed in the Experimental section, and the results are assembled in Table 3. The significance of the results of all these measurements is discussed later (p. 1916).

EXPERIMENTAL

Picrates were crystallised from aqueous ethanol containing picric acid, unless otherwise stated. Equivalent weights determined by titration of free bases are denoted by e.w. (b), and those determined by titration of amine picrates with perchloric acid in acetic acid by e.w. (p).

NN-*Dialkylethylenediamines.*—*NN*-Dimethylethylenediamine was prepared by an adaptation of the method of Bloom, Breslow, and Hauser,[2] *i.e.*, by reduction of dimethylaminomethyl cyanide (prepared by Turner's method [4]) with sodium and butan-1-ol in toluene. After steam-distillation, the amine was extracted from the toluene with hydrochloric acid, then liberated with 40% w/v aqueous sodium hydroxide. The oily base was separated and more was extracted from the aqueous layer with ether. After drying (KOH) and removal of ether, the combined

[4] Turner, *J. Amer. Chem. Soc.*, 1946, **68**, 1607.

XUM

TABLE 1. NN-*Dialkyl*-N′-*arylalkylethylenediamines*, $R_2N{\cdot}[CH_2]_2{\cdot}NH{\cdot}C_6H_4R'$-*p*.

(All compounds are new except those indicated by a reference in the last column.)

R	R′	Dipicrate (P_2) * or dihydrochloride (Cl_2)	M. p. or b. p./mm. (°c)	n_D^{18}	Found (%) C	H	N	Hal	e.w. (p)	Formula	Required (%) C	H	N	Hal	e.w.	Yield (%)	Ref.
Me	H	—	82—83/0·3 [a]	1·5183 [a]	74·3	10·0	15·7	—	90	$C_{11}H_{18}N_2$	74·1	10·1	15·7	—	89	50	11, 12
Me	,,	P_2	162—164 [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	12
Me	,,	Cl_2	205—206 [c]	—	—	—	—	—	—	—	—	—	—	—	—	—	13
Me	Me	—	92—96/0·25	1·5105	75·1	10·5	14·3	—	95	$C_{12}H_{20}N_2$	74·9	10·5	14·6	—	96	55	—
Me	,,	P_2	176—176·5	—	44·3	4·0	17·2	—	—	$C_{24}H_{26}N_8O_{14}$	44·3	4·0	17·2	—	—	—	—
Me	OMe	—	114—116/0·8 [d]	1·5163 [d]	69·2	9·5	13·4	—	104	$C_{12}H_{20}N_2O$	69·4	9·6	13·5	—	104	50	*j*
Me	,,	P_2	156—157 [e]	—	43·3	3·9	16·8	—	—	$C_{24}H_{26}N_8O_{15}$	43·2	3·9	16·8	—	—	—	*k*
Me	F	—	92—95/0·7	1·4949	67·7	8·7	14·2	—	98	$C_{11}H_{17}FN_2$	67·3	8·8	14·3	—	98	52	—
Me	,,	P_2	164·5—165·5	—	42·2	3·6	17·2	—	—	$C_{23}H_{23}FN_8O_{14}$	42·2	3·5	17·1	—	—	—	—
Me	Cl	—	92—95/0·4 [f]	1·5248 [f]	61·8	7·7	13·0	16·9	107	$C_{11}H_{17}ClN_2$	62·1	8·0	13·2	16·7	106	53	*j*
Me	,,	P_2	163·5—164	—	41·0	3·6	16·9	5·3	—	$C_{23}H_{23}ClN_8O_{14}$	41·2	3·5	16·7	5·3	—	—	—
Me	Br	—	120—124/0·8	1·5405	51·8	6·7	10·6	31·4	128	$C_{11}H_{17}BrN_2$	51·4	6·6	10·9	31·1	128·5	50	—
Me	,,	P_2	192—194	—	38·9	3·3	15·3	11·3	—	$C_{23}H_{23}BrN_8O_{14}$	38·6	3·2	15·7	11·2	—	—	—
Et	H	—	112—114/0·6 [g]	1·5047 [g]	75·6	10·6	13·8	—	102	$C_{13}H_{22}N_2$	75·7	10·7	13·6	—	103	61	1
Et	,,	P_2	171·5—172	—	45·2	4·3	16·7	—	—	$C_{25}H_{28}N_8O$	45·2	4·2	16·9	—	—	—	—
Et	Me	—	131—132/6	1·5064	76·7	11·0	12·4	—	109	$C_{14}H_{24}N_2$	76·4	10·9	12·7	—	110	60	—
Et	,,	P_2	171·5—172·5	—	46·8	4·4	16·5	—	—	$C_{26}H_{30}N_8O_{14}$	46·0	4·5	16·5	—	—	—	—
Et	OMe	—	140—142/1·0 [h]	1·5108	71·6	10·3	11·6	—	118	$C_{14}H_{24}N_2O$	71·2	10·2	11·9	—	118	52	*l*
Et	,,	P_2	149·5—150·5 [i]	—	45·0	4·2	16·1	—	—	$C_{26}H_{30}N_8O_{15}$	45·0	4·4	16·1	—	—	—	*kl*
Et	F	—	96—100/0·5	1·4918	69·8	9·4	12·3	—	112	$C_{13}H_{21}FN_2$	69·7	9·4	12·5	—	112	54	—
Et	,,	P_2	150—151	—	44·3	4·0	16·4	—	—	$C_{25}H_{27}FN_8O_{14}$	44·0	4·0	16·4	—	—	—	—
Et	Cl	—	126—128/0·7	1·5190	65·0	8·8	11·7	14·7	120	$C_{13}H_{21}ClN_2$	64·8	8·8	11·6	14·7	120	63	—
Et	,,	P_2	137—139	—	43·0	3·8	16·4	5·0	—	$C_{25}H_{27}ClN_8O_{14}$	43·0	3·9	16·0	5·1	—	—	—
Et	Br	—	132—134/0·5	1·5337	54·5	7·3	9·8	26·2	142	$C_{13}H_{21}BrN_2$	54·7	7·4	9·8	26·0	143	68	—
Et	,,	P_2	155·5—157	—	40·6	3·9	14·7	11·0	—	$C_{25}H_{27}BrN_8O_{14}$	40·4	3·7	15·1	11·0	—	—	—

[a] Lit.,[11] b. p. 128—132°/18 mm.; lit.,[12] n_D^{25} 1·507. [b] Lit.,[13] m. p. 162—164°. [c] Lit.,[13] m. p. 205—207°. [d] Lit.,[j] b. p. 106—107°/0·52 mm., n_D^{25} 1·5148. [e] Lit.,[k] m. p. 151·5—153·5°. [f] Lit.,[j] b. p. 95—97°/0·47 mm., n_D^{25} 1·5198. [g] Lit.,[1] b. p. 115—119°/0·5 mm., n_D 1·499. [h] Lit.,[l] b. p. 203—205°/18 mm. [i] Lit.,[k] m. p. 150—151°; lit.,[l] m. p. 140—141°. [j] U.S.P. 2,582,292/1945 (*Chem. Abs.*, 1952, **46**, 10,202). [k] Matsuka, Shirakawa, and Kawasaki, *J. Pharm. Soc. Japan*, 1951, **71**, 1316 (*Chem. Abs.*, 1952, **46**, 7101). [l] Wojahn and Erdelmeier, *Arch. Pharm.*, 1942, **200**, 215.

* Dipicrates (Table 1) recryst. from aq. EtOH.

TABLE 2. NN-*Dialkyl*-N′-*arylalkyl*-N′-*heterocyclic ethylenediamines*, $R_2N{\cdot}[CH_2]_2{\cdot}NR''{\cdot}C_6H_4R'$-*p*.

R	R′	R″	Dipicrate (P_2) or mono- (Cl_1) or di-hydrochloride (Cl_2)	M. p. or b. p./mm. (°c)	Found (%) C	H	N	Hal	e.w. (b)	e.w. (p)	Formula	Required (%) C	H	N	Hal	e.w.	Yield (%)
Me	H	A	—	200—204/0·8	72·5	7·1	17·9	—	148	154	$C_{19}H_{22}N_4$	74·5	7·2	18·3	—	153	42
Me	,,	A	Cl_1	194—195·5	66·2	6·8	16·8	10·5	—	—	$C_{19}H_{23}ClN_4$	66·6	6·7	16·4	10·4	—	28
Me	,,	A	Cl_2[a]	215—216	—	—	—	18·4	—	—	$C_{19}H_{24}Cl_2N_4$	—	—	—	18·7	—	—
Me	,,	A	P_2	214—216	48·7	3·8	18·2	—	—	—	$C_{31}H_{28}N_{10}O_{14}$	48·7	3·7	18·3	—	—	—
Me	Me	A	Cl_1	201—202	67·7	7·2	15·9	9·95	159	158	$C_{20}H_{25}ClN_4$	67·3	7·1	15·7	9·94	160	42
Me	,,	A	P_2	199—200·5	49·6	3·9	17·9	—	—	—	$C_{32}H_{30}N_{10}O_{14}$	49·4	3·9	18·0	—	—	—
Me	OMe	A	—	186—190/0·008	—	—	—	—	174	169	$C_{20}H_{24}N_4O$	—	—	—	—	168	38
Me	,,	A	P_2	193—194	48·5	3·8	17·5	—	—	—	$C_{32}H_{30}N_{10}O_{15}$	48·4	3·8	17·6	—	—	—
Me	F	A	—	172—176/0·01	68·9	6·2	16·8	—	158	162	$C_{19}H_{21}FN_4$	70·3	6·5	17·3	—	162	54
Me	,,	A	P_2	217—218	47·4	3·7	17·8	—	—	—	$C_{31}H_{27}FN_{10}O_{14}$	47·6	3·5	17·9	—	—	—
Me	Cl	A	—	170—174/0·03	—	—	—	—	178	172	$C_{19}H_{21}ClN_4$	—	—	—	—	170	33
Me	,,	A	P_2	209·5—211	46·5	3·6	17·2	4·4	—	—	$C_{31}H_{27}ClN_{10}O_{14}$	46·6	3·4	17·5	4·4	—	—
Me	Br	A	—	176—180/0·005	—	—	—	—	187	191	$C_{19}H_{21}BrN_4$	—	—	—	—	193	27
Me	,,	A	P_2	222·5—224	44·4	3·3	16·6	9·6	—	—	$C_{31}H_{27}BrN_{10}O_{14}$	44·1	3·2	16·6	9·5	—	—
Et	H	A	—	200—205/0·3	—	—	—	—	166	166	$C_{21}H_{26}N_4$	—	—	—	—	167	42
Et	,,	A	Cl_1[a]	142·5—143·5	—	—	—	—	—	—	$C_{21}H_{27}ClN_4$	—	—	—	9·6	—	—
Et	,,	A	Cl_2[a]	231—233	61·9	7·2	13·7	17·4	—	—	$C_{21}H_{28}Cl_2N_4$	62·1	6·9	13·8	17·4	—	—
Et	,,	A	P_2	169—170	49·4	4·2	17·8	—	—	—	$C_{33}H_{32}N_{10}O_{14}$	50·0	4·0	17·7	—	—	—
Et	Me	A	—	174—176/0·005	—	—	—	—	176	174	$C_{22}H_{28}N_4$	—	—	—	—	174	59
Et	,,	A	P_2	201—202	50·1	4·1	17·3	—	—	—	$C_{34}H_{34}N_{10}O_{14}$	50·6	4·3	17·4	—	—	—
Et	OMe	A	—	184—188/0·007	—	—	—	—	188	181	$C_{22}H_{28}N_4O$	—	—	—	—	182	35
Et	,,	A	P_2	173—174	49·6	4·4	16·8	—	—	—	$C_{34}H_{34}N_{10}O_{15}$	49·6	4·2	17·0	—	—	—
Et	F	A	—	178—180/0·008	—	—	—	—	173	178	$C_{21}H_{25}FN_4$	—	—	—	—	176	71
Et	,,	A	P_2	201·5—202	48·4	4·1	17·5	—	—	—	$C_{33}H_{31}FN_{10}O_{14}$	48·9	3·9	17 3	—	—	—
Et	Cl	A	—	192—196/0·005	—	—	—	—	181	185	$C_{21}H_{25}ClN_4$	—	—	—	—	184	68
Et	,,	A	P_2	201·5—202	48·0	4·0	17·2	4·2	—	—	$C_{33}H_{31}ClN_{10}O_{14}$	47·9	3·8	16·9	4·3	—	—
Et	Br	A	—	200—204/0·01	—	—	—	—	205	206	$C_{21}H_{25}BrN_4$	—	—	—	—	207	72
Et	,,	A	P_2	201·5—203	45·2	3·9	16·5	8·9	—	—	$C_{33}H_{31}BrN_{10}O_{14}$	45·5	3·6	16·1	9·2	—	—
Me	H	B	—	135—139/0·02	—	—	—	—	130	134	$C_{16}H_{22}N_4$	—	—	—	—	135	26
Me	,,	B	P_2	161—162·5	46·2	3·8	19·3	—	—	—	$C_{28}H_{28}N_{10}O_{14}$	46·2	3·9	19·2	—	—	—
Me	Me	B	—	134—140/0·005	—	—	—	—	144	141	$C_{17}H_{24}N_4$	—	—	—	—	142	35
Me	,,	B	P_2	184—185	47·0	4·1	18·9	—	—	—	$C_{29}H_{30}N_{10}O_{14}$	46·9	4·0	18·9	—	—	—
Me	OMe	B	—	158—166/0·01	—	—	—	—	145	149	$C_{17}H_{24}N_4O$	—	—	—	—	150	34
Me	,,	B	P_2	142—144	45·6	4·0	18·4	—	—	—	$C_{29}H_{30}N_{10}O_{15}$	45·9	4·0	18·5	—	—	—
Me	F	B	—	123—125/0·002	—	—	—	—	146	144	$C_{16}H_{21}FN_4$	—	—	—	—	144	28
Me	,,	B	P_2	189·5—190	45·2	3·6	18·8	—	—	—	$C_{28}H_{27}FN_{10}O_{14}$	45·0	3·7	18·8	—	—	—
Me	Cl	B	—	147—152/0·01	—	—	—	—	145	150	$C_{16}H_{21}ClN_4$	—	—	—	—	152	29
Me	,,	B	P_2	172·5—174·5	44·0	3·6	18·7	4·7	—	—	$C_{28}H_{27}ClN_{10}O_{14}$	44·1	3·6	18·4	4·7	—	—
Me	Br	B	—	148—152/0·01	—	—	—	—	182	174	$C_{16}H_{21}BrN_4$	—	—	—	—	175	27
Me	,,	B	P_2	139—141	41·4	3·4	17·1	10·0	—	—	$C_{28}H_{27}BrN_{10}O_{14}$	41·2	3·4	17·3	9·9	—	—
Et	H	B	—	130—136/0·001	—	—	—	—	144	146	$C_{18}H_{26}N_4$	—	—	—	—	149	54

TABLE 2. (*Continued.*)

R	R′	R″	Dipicrate (P_2) or mono- (Cl_1) or di-hydrochloride (Cl_2)	M. p. or b. p./mm. (°c)	Found (%) C	H	N	Hal	e.w. (b)	e.w. (p)	Formula	Required (%) C	H	N	Hal	e.w.	Yield (%)
Et	,,	B	P_2	144—145	47·6	4·3	18·5	—	—	—	$C_{30}H_{32}N_{10}O_{14}$	47·6	4·3	18·5	—	—	—
Et	Me	B	Cl_2	142—145/0·001	—	—	—	—	149	154	$C_{19}H_{26}N_4$	—	—	—	—	156	56
Et	,,	B	P_2	192—193	48·3	4·6	18·4	—	—	—	$C_{31}H_{34}N_{10}O_{14}$	48·1	4·5	18·2	—	—	—
Et	OMe	B	Cl_2	155—162/0·003	—	—	—	—	168	165	$C_{19}H_{26}N_4O$	—	—	—	—	165	76
Et	,,	B	P_2	162·5—163·5	47·0	4·4	17·7	—	—	—	$C_{31}H_{34}N_{10}O_{15}$	47·3	4·3	17·8	—	—	—
Et	F	B	Cl_2	138—140/0·002	—	—	—	—	158	160	$C_{18}H_{23}FN_4$	—	—	—	—	158	63
Et	,,	B	P_2	160·5—161·5	46·6	4·2	18·4	—	—	—	$C_{30}H_{31}FN_{10}O_{14}$	46·5	4·0	18·1	—	—	—
Et	Cl	B	Cl_2	154—156/0·003	—	—	—	—	168	165	$C_{18}H_{23}ClN_4$	—	—	—	—	166	48
Et	,,	B	P_2	163·5—166	45·6	4·1	17·9	4·7	—	—	$C_{30}H_{31}ClN_{10}O_{14}$	45·5	4·0	17·7	4·5	—	—
Et	Br	B	Cl_2	158—162/0·003	—	—	—	—	182	187	$C_{18}H_{23}BrN_4$	—	—	—	—	189	64
Et	,,	B	P_2	176—176·5	43·1	3·9	16·5	9·4	—	—	$C_{30}H_{31}BrN_{10}O_{14}$	43·1	3·7	16·8	9·6	—	—
Me	H	C	Cl_2	94—96/0·008[b]	—	—	—	—	134	133	$C_{16}H_{22}N_4$	—	—	—	—	135	18
Me	,,	C	P_2	136—138	46·4	3·7	19·0	—	—	—	$C_{28}H_{28}N_{10}O_{14}$	46·2	3·9	19·2	—	—	—
Me	Me	C	Cl_2	94—96/0·001	—	—	—	—	144	144	$C_{17}H_{24}N_4$	—	—	—	—	142	14
Me	,,	C	P_2	164—165·5	46·7	4·1	19·0	—	—	—	$C_{29}H_{30}N_{10}O_{14}$	46·9	4·0	18·9	—	—	—
Me	OMe	C	Cl_2	122—124/0·001	—	—	—	—	158	148	$C_{17}H_{24}N_4O$	—	—	—	—	150	26
Me	,,	C	P_2	140—141	46·0	3·9	18·2	—	—	—	$C_{29}H_{30}N_{10}O_{15}$	45·9	4·0	18·5	—	—	—
Me	F	C	Cl_2	94—104/0·005	—	—	—	—	149	144	$C_{16}H_{21}FN_4$	—	—	—	—	144	40
Me	,,	C	P_2	160·5—161	44·7	3·4	18·5	—	—	—	$C_{28}H_{27}FN_{10}O_{14}$	45·0	3·6	18·8	—	—	—
Me	Cl	C	Cl_2	110—112/0·001	—	—	—	—	148	150	$C_{16}H_{21}ClN_4$	—	—	—	—	152	30
Me	,,	C	P_2	163—164	44·2	3·8	18·7	5·0	—	—	$C_{28}H_{27}ClN_{10}O_{14}$	44·1	3·6	18·4	4·7	—	—
Me	Br	C	Cl_2	110—118/0·003	—	—	—	—	176	174	$C_{16}H_{21}BrN_4$	—	—	—	—	175	26
Me	,,	C	P_2	165—166	41·9	3·1	17·7	10·0	—	—	$C_{28}H_{27}BrN_{10}O_{14}$	41·6	3·4	17·3	9·9	—	—
Et	H	C	Cl_2	106—108/0·003	—	—	—	—	150	147	$C_{18}H_{26}N_4$	—	—	—	—	149	56
Et	,,	C	P_2	138·5—140	47·4	4·4	18·2	—	—	—	$C_{30}H_{32}N_{10}O_{14}$	47·6	4·3	18·5	—	—	—
Et	Me	C	Cl_2	104—106/0·002	—	—	—	—	150	157	$C_{19}H_{28}N_4$	—	—	—	—	156	49
Et	,,	C	P_2	135—137	48·4	4·5	18·2	—	—	—	$C_{31}H_{34}N_{10}O_{14}$	48·3	4·5	18·2	—	—	—
Et	OMe	C	Cl_2	122—124/0·0005	—	—	—	—	167	166	$C_{19}H_{28}N_4O$	—	—	—	—	164	36
Et	,,	C	P_2	134—135·5	47·1	4·2	18·1	—	—	—	$C_{31}H_{34}N_{10}O_{15}$	47·3	4·4	17·8	—	—	—
Et	F	C	Cl_2	105—108/0·001	—	—	—	—	154	158	$C_{18}H_{25}FN_4$	—	—	—	—	158	53
Et	,,	C	P_2	176—176·5	46·7	4·0	18·1	—	—	—	$C_{30}H_{31}FN_{10}O_{14}$	46·5	4·0	18·1	—	—	—
Et	Cl	C	Cl_2	105—110/0·005	—	—	—	—	173	164	$C_{18}H_{25}ClN_4$	—	—	—	—	166	43
Et	,,	C	P_2	169—170	45·7	4·2	17·7	4·5	—	—	$C_{30}H_{31}ClN_{10}O_{14}$	45·5	4·0	17·7	4·5	—	—
Et	Br	C	Cl_2	128—132/0·0005	—	—	—	—	193	191	$C_{18}H_{25}BrN_4$	—	—	—	—	189	44
Et	,,	C	P_2	167—167·5	43·5	3·8	17·1	9·5	—	—	$C_{30}H_{31}BrN_{10}O_{14}$	43·1	3·8	16·8	9·6	—	—

A = 4-Quinazolyl. B = 6-Methyl-4-pyrimidyl. C = 4-Methyl-2-pyrimidyl.
Picrates were crystallised from aqueous acetone.

[a] Prepared by adding the required quantity of an ethanolic solution of hydrogen chloride to an ethanolic solution of the base and precipitating the salt with ether. The salt was crystallised from nitromethane. [b] B.P. 629,471/1946 lists b. p. 134°/1·4 mm. All the other compounds listed in Table 2 are new.

bases were distilled to give *NN*-dimethylethylenediamine, b. p. 106—109° (lit.,[4] 105—108°) [derived phenylthiourea, m. p. 82—82·5° (lit.,[4] 82·6—83°), in 48% overall yield. This base was also prepared by methylation and subsequent hydrolysis of monoacetylethylenediamine, prepared by Aspinall's method,[5] according to the method of Baldy, Naudet, and Desnouelle [6] (overall yield 46%). *NN*-Diethylethylenediamine was obtained from L. Light and Company and had b. p. 144—145°.

Substituted Benzaldehydes.—4-Bromo-, m. p. 57° (lit.,[7] 57°), and 4-fluoro-benzaldehyde, b. p. 180—181°/760 mm. (lit.,[8] 181·5°/763 mm.) [oxime, m. p. 86—87° (lit.,[8] 86·5°)], were prepared by Beech's method.[3]

NN-*Dialkyl*-N′-*arylalkylethylenediamines.*—*N*′-Benzylidene-*NN*-dimethylethylenediamine was prepared (76%) by condensing benzaldehyde with 2-dimethylaminoethylamine by Surrey's method [9] and had b. p. 83°/0·3 mm., n_D^{18} 1·5347 (lit., 132—133°/12 mm., n_D^{25} 1·5330). This was then reduced by a modification of Alexander and Wildman's method.[10] To a mixture of the anil (0·19 mole) and triethylamine (0·4 mole) was added 98—100% formic acid (0·6 mole) and, after the initial reaction had subsided, excess of triethylamine and water were distilled off through a column and the residue was heated strongly until evolution of carbon dioxide ceased. 6N-Hydrochloric acid (200 ml.) was added, and the mixture was boiled for 15 min., and, after cooling, basified with 5N-sodium hydroxide. The oily layer was separated, more oil was extracted from the aqueous layer with ether, and the ether was removed. The combined oils were distilled to give *N*′-benzyl-*NN*-dimethylethylenediamine (76%), b. p. 82—83°/0·3 mm., n_D^{18} 1·5183 (lit.,[11,12] 128—132°/18 mm., n_D^{25} 1·507) [Found: C, 74·3; H, 10·1; N, 15·7%; e.w. (p), 90. Calc. for $C_{11}H_{18}N_2$: C, 74·1; H, 10·1; N, 15·7%; e.w., 89] [dipicrate, m. p. 162—164° (lit.,[12] 162—164°); dihydrochloride (from ethanol), m. p. 205—206° (lit.,[13] 205—207°)]. This amine was also prepared by a modification of a method given in a patent [14] (yield 12%) and by Zechmeister and Truka's method [15] (yield 64%). The compounds listed in Table 1 were prepared as for *N*′-benzyl-*NN*-dimethylethylenediamine, but without isolation of the intermediate anil.

Chloro-heterocyclic Compounds.—4-Chloroquinazoline was prepared by Chapman, Gibson, and Mann's method,[16] and 4-chloro-6-methyl- and 2-chloro-4-methyl-pyrimidine according to the methods given by Chapman and Rees,[17] and had m. p.s as recorded by these authors.

NN-*Dialkyl*-N′-*arylalkyl*-N′-*heterocyclic Ethylenediamines.*—4-Chloroquinazoline (0·013 mole) and *N*′-benzyl-*NN*-dimethylethylenediamine (0·013 mole) were boiled under reflux in nitromethane (10 ml.) for 2 hr. Adding acetone (20 ml.) led to a white precipitate which was crystallised from nitromethane to give N-*benzyl*-N′N′-*dimethyl*-N-4-*quinazolylethylenediamine monohydrochloride* (28%), m. p. 194—195·5° (Found: C, 66·2; H, 6·8; Cl, 10·5; N, 16·8. $C_{19}H_{22}N_4$,HCl requires C, 66·6; H, 6·7; Cl, 10·4; N, 16·4%). Similarly 4-chloroquinazoline and the *N*-4-methylbenzylamine gave N-p-*methylbenzyl*-N′N′-*dimethyl*-N-4-*quinazolylethylenediamine monohydrochloride* (42%), m. p. 201—202° (Found: C, 67·7; H, 7·2; Cl, 9·95; N, 15·9. $C_{20}H_{24}N_4$,HCl requires C, 67·3; H, 7·1; Cl, 9·9; N, 15·7%).

4-Chloroquinazoline and *N*′-benzyl-*NN*-dimethylethylenediamine were also heated together without solvent at 120—130° for 4 hr. The semi-solid product was dissolved in hot 95% ethanol, the solution was made alkaline with sodium hydroxide and the liberated oil was extracted with ether. After drying (KOH) the ether was removed and the residue was distilled to give N-*benzyl*-N′N′-*dimethyl*-N-4-*quinazolylethylenediamine*, b. p. 200—204°/0·8 mm. [Found: C, 72·5; H, 7·1; N, 17·9%; e.w. (b) 148; e.w. (p), 154. $C_{19}H_{22}N_4$ requires C, 74·5; H, 7·2; N, 18·3%; e.w. 153] [*dipicrate* (from acetone), m. p. 214—216° (Found: C, 48·7; H, 3·8; N, 18·2. $C_{31}H_{28}N_{10}O_{14}$ requires C, 48·7; H, 3·7; N, 18·3%)]. The remaining quinazoline derivatives

[5] Aspinall, *J. Amer. Chem. Soc.*, 1941, **63**, 853.
[6] Baldy, Naudet, and Desnouelle, *Bull. Soc. chim. France*, 1955, 518.
[7] Kjellin and Kuylenstjerna, *Ber.*, 1897, **30**, 1899.
[8] Shoesmith, Sosson, and Slater, *J.*, 1926, 2760.
[9] Surrey, *J. Amer. Chem. Soc.*, 1949, **71**, 3105.
[10] Alexander and Wildman, *J. Amer. Chem. Soc.*, 1948, **70**, 1187.
[11] B.P. 594,603, 606,181—2/1945.
[12] U.S.P. 2,440,703/1948; cf. *Chem. Abs.*, 1949, **43**, 1914.
[13] Gardner and Stevens, *J. Amer. Chem. Soc.*, 1949, **71**, 1869.
[14] B.P. 433,625/1934.
[15] Zechmeister and Truka, *Ber.*, 1930, **63**, 2883.
[16] Chapman, Gibson, and Mann, *J.*, 1947, 890.
[17] Chapman and Rees, *J.*, 1954, 1190.

XUM

listed in Table 2 were prepared in this way, as was N-*benzyl*-N'N'-*dimethyl*-N-6-*methyl*-4-*pyrimidylethylenediamine*. The remaining pyrimidine derivatives listed in Table 2 were prepared by boiling the appropriate chloroheterocyclic compound and amine under reflux in sufficient 0·5N-acetic acid to neutralise one basic centre in the amine for the 4-methyl-2-pyrimidyl derivatives, and in water for the 6-methyl-4-pyrimidyl derivatives. The products were worked up as for *N*-benzyl-*N'N'*-dimethyl-*N*-4-quinazolylethylenediamine.

Measurement of Absorption Spectra.—Ultraviolet absorption was measured for *N'*-benzyl-*NN*-dimethylethylenediamine, *N*-benzyl-*N'N'*-dimethyl-*N*-4-quinazolylethylenediamine, and for 4-benzylaminoquinazoline (m. p. 169—169·5°) with a Unicam S.P. 500 spectrophotometer. The two ethylenediamine derivatives were investigated in three states: as the free base (in 0·1N-sodium hydroxide), as the singly protonated ion (in a buffer solution of pH 6·8), and as the doubly protonated ion (in 0·1N-hydrochloric acid), the solvents having been chosen from titration results. For 4-benzylaminoquinazoline the solvents used were 0·1N-sodium hydroxide and 0·1N-hydrochloric acid.

The absorption curves obtained for *N*-benzyl-*N'N'*-dimethylethylenediamine in all three solvents were very similar to each other and to that of benzylamine in acid solution.[18] Those obtained for the two quinazoline compounds are shown in Figs. 1 and 2.

Determination of pK_a *Values and Equivalent Weights of Bases.*—In order to approximate to physiological conditions the pK_a values of the conjugate acids of the ditertiary bases were determined by titration in aqueous solution at 37°. To keep the free bases in solution during titration, dilute solutions were necessary, requiring a small volume of titrant which was added from an Agla micrometer syringe. To ensure complete dissolution of the base it was dissolved in hydrochloric acid, and the solution was diluted with water and then titrated with 0·1N-barium hydroxide, the liquid being stirred with a stream of nitrogen.

To calculate dissociation constants, Gage's method [19] was adapted for dibasic acids (although four potentially basic centres are present in the ditertiary amines, only two become protonated in dilute aqueous solution). The dissociation of unsymmetrical dibasic acids has been considered by Adams [20] whose analysis, combined with conservation of mass and charge, leads to equation (i) (cf. Barton,[21] from whose equation the same relation may be derived):

$$(c - x) = x[\mathrm{H}]/(K_1 + K'_1) - K_2K'_2(2c - x)/[\mathrm{H}](K_2 + K'_2) \quad . \quad . \quad . \quad \text{(i)}$$

where c = total molar concentration of acid and derived species, $x = [\mathrm{M}] + [\mathrm{H}] - [\mathrm{OH}]$, [M] = normality in the titrated liquid of added titrant cation, [H] = hydrogen-ion concentration, [OH] = hydroxyl-ion concentration. K_1 and K'_1 are dissociation constants for the alternative first stages of ionisation of the dibasic acid. K_2 and K'_2 are dissociation constants for the alternative second stages of ionisation of the dibasic acid. Equation (i) is inexact in that activity coefficients have not been introduced. At concentrations used (~0·0001N), the error is not significant.

The dibasic acids investigated in this work have as one acid centre a protonated aromatic amino-group and as the other a protonated aliphatic amino-group. It is expected that the dissociation constant of the former would be much greater than that of the latter which could thus reasonably be neglected in their sum. If K_1 and K'_2 refer to the aromatic basic centre and K_2 and K'_1 to the aliphatic basic centre then equation (i) reduces to (ii)

$$c - x = x[\mathrm{H}]/K_1 - K_2(2c - x)/[\mathrm{H}] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(ii)}$$

When $K_1 \gg K_2$ for dibasic acids the two stages of neutralisation are virtually separate. When this is so, the two terms on the right-hand side of equation (ii) correspond to the two stages of neutralisation, the first term being negligible during the second stage and the second term during the first stage. Equation (ii) can thus be modified to (iii) and (iv) which apply to the two successive stages of neutralisation:

$$(c - x) = x[\mathrm{H}]/K_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iii)}$$

$$(c - x) = -K_2(2c - x)/[\mathrm{H}] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iv)}$$

[18] Controulis, Rebstock, and Crooks, *J. Amer. Chem. Soc.*, 1949, **71**, 2463.
[19] Gage, *Analyst*, 1957, **82**, 219.
[20] Adams, *J. Amer. Chem. Soc.*, 1916, **38**, 1503.
[21] Barton, *Nature*, 1947, **160**, 752.

Equation (iii) is identical with that given by Gage [19] for a monobasic acid. As shown by him, a plot of x[H] against x should give a straight line of slope $-K_1$ and extrapolation to x[H] = 0 should give $x = c$, from which the equivalent weight may be calculated. Similarly a plot of $-(c - x)$[H] against x should be linear and of slope $-K_2$. Extrapolation to $-(c - x)$[H] = 0 should give $x = 2c$ to serve as a check on c.

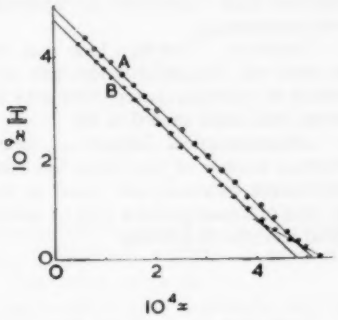


FIG. 3. *Derived curves for first stage of titration of* N-*benzyl*-N′N′-*dimethyl*-N-4-*quinazolylethylenediamine.*

A, *Crystalline dihydrochloride.* B, *Neutralised distilled base.*

TABLE 3. *Physical data, etc., for* NN-*dialkyl*-N′-*arylalkyl*-N′-*heterocyclic ethylenediamines,* $R_2N{\cdot}[CH_2]_2{\cdot}NR'R''$.

No.	R	R′	R″	n_D^{18}	Dissociation Constant pK_{a_2}	Dissociation Constant pK_{a_1}	Potency [a] 10^3 ED_{50}
1	Me	Benzyl	A	1·6027	5·0	8·5	8·0
2	Me	*p*-Methylbenzyl	A	—	5·0	8·5	in.
3	Me	*p*-Methoxybenzyl	A	1·6133	5·0	8·5	6·7
4	Me	*p*-Fluorobenzyl	A	1·6055	4·8	8·5	5·1
5	Me	*p*-Chlorobenzyl	A	1·6208	4·8	8·5	2·7
6	Me	*p*-Bromobenzyl	A	1·6290	4·9	8·4	0·8
7	Et	Benzyl	A	1·5975	4·9	9·0	4·8
8	Et	*p*-Methylbenzyl	A	1·5994	4·8	8·9	p.
9	Et	*p*-Methoxybenzyl	A	1·6048	4·8	8·9	in.
10	Et	*p*-Fluorobenzyl	A	1·5927	4·7	8·9	in.
11	Et	*p*-Chlorobenzyl	A	1·6083	4·8	8·8	4·9
12	Et	*p*-Bromobenzyl	A	1·6190	4·8	8·6	1·6
13	Me	Benzyl	B	1·5565	5·2	8·3	0·4
14	Me	*p*-Methylbenzyl	B	1·5500	5·1	8·3	—
15	Me	*p*-Methoxybenzyl	B	1·5644	5·1	8·3	0·15
16	Me	*p*-Fluorobenzyl	B	1·5442	5·2	8·2	—
17	Me	*p*-Chlorobenzyl	B	1·5603	5·2	8·1	—
18	Me	*p*-Bromobenzyl	B	1·5688	5·2	8·0	0·2
19	Et	Benzyl	B	1·5498	5·2	8·8	1·7
20	Et	*p*-Methylbenzyl	B	1·5517	5·2	8·8	—
21	Et	*p*-Methoxybenzyl	B	1·5538	5·1	8·8	—
22	Et	*p*-Fluorobenzyl	B	1·5402	5·2	8·8	—
23	Et	*p*-Chlorobenzyl	B	1·5503	5·1	8·7	—
24	Et	*p*-Bromobenzyl	B	1·5667	5·2	8·7	0·9
25	Me	Benzyl	C	1·5576	2·9	8·6	2·0
26	Me	*p*-Methylbenzyl	C	1·5548	2·9	8·7	—
27	Me	*p*-Methoxybenzyl	C	1·5621	2·9	8·6	0·1
28	Me	*p*-Fluorobenzyl	C	1·5438	3·1	8·5	—
29	Me	*p*-Chlorobenzyl	C	1·5619	3·0	8·4	—
30	Me	*p*-Bromobenzyl	C	1·5690	3·0	8·3	1·0
31	Et	Benzyl	C	1·5490	2·8	9·2	10
32	Et	*p*-Methylbenzyl	C	1·5480	2·8	9·1	—
33	Et	*p*-Methoxybenzyl	C	1·5542	2·8	9·1	—
34	Et	*p*-Fluorobenzyl	C	1·5413	2·8	8·9	—
35	Et	*p*-Chlorobenzyl	C	1·5508	2·8	8·9	—
36	Et	*p*-Bromobenzyl	C	1·5672	2·9	8·8	4·5
		Thonzylamine	—	—	—	—	0·093

A, B, C, as for Table 2. in. = inactive. p. = potentiates the action of histamine.

[a] Antihistamine activity determined by the guinea-pig aerosol method, ED_{50} in millimoles per kg. pK_{a_2} refers to the dialkylamino-group, and pK_{a_1} refers to a ring nitrogen atom.

XUM

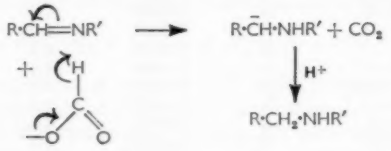
These predictions were found to be correct in practice, straight lines being obtained from the two plots. Moreover, the presence of small amounts of other basic impurities in the ditertiary bases did not invalidate the method, their presence being shown by a break in the straight line near the end of each stage of neutralisation. This is illustrated in Fig. 3 which shows the curves obtained by titrating separately the crystalline dihydrochloride and the distilled base (dissolved in hydrochloric acid) of *N*-benzyl-*N'N'*-dimethyl-*N*-4-quinazolylethylenediamine.

Procedure. The free base was dissolved in a quantity of N-hydrochloric acid calculated to form the dihydrochloride, and an equal volume of acetone. 0·8 ml. of this solution was added to distilled water (39·0 ml.) at 37° and titrated with 0·1N-barium hydroxide, the pH being read after each 0·01 ml.

Pharmacological Results.—A range of pharmacological properties of a number of the ditertiary amines of this series has been studied and has been reported elsewhere.[23] The antihistaminic potencies are listed in Table 3. The compounds studied have toxicities similar to that of Thonzylamine and in addition those derived from 2-aminopyrimidine have marked local anæsthetic activity.

Discussion

Reduction of Anils by Formic Acid.—In this work reduction has always taken place in the presence of an excess of free base and has been shown to do so when base is present in large excess (by adding formic acid dropwise during the reduction). Thus it is probably the formate ion which is the reducing species. The excess of free base and the anhydrous conditions used make it unlikely that either of the mechanisms postulated by Staple and Wagner [23] (initial protonation or hydration to an aminohydrin) is correct. It is suggested that the first step is a hydride-ion transfer from formate ion to the polarised reaction centre, following by proton uptake to complete the reduction.

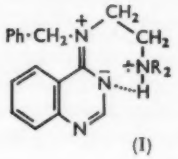


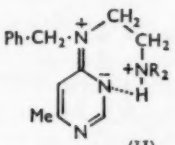
Dissociation Constants and Structure.—The pK_a values listed in Table 3 show expected trends in the main. The pK_{a_2} values in each diethylamine are greater than for the corresponding dimethylamines, as is usual. The effect of the heterocyclic group, as found in pK_{a_1} values, is in accord with the results of Albert, Goldacre, and Phillips,[24] and of Brown and Short.[25] However the effect of the heterocyclic group on the pK_{a_2} values is unexpected. This is large enough and constant enough for each heterocyclic group for an explanation to be sought. Comparison of pK_{a_1} and pK_{a_2} values for the three heterocyclic groups shows that a given group affects the two dissociation constants in the opposite direction, *e.g.*, the 4-methyl-2-pyrimidyl group gives the lowest pK_{a_1} values and the highest pK_{a_2} values. The effect is therefore unlikely to be due to an inductive mechanism which would affect both acid centres in the same way. It may however be explained in terms of an intramolecular hydrogen-bonded structure for the monoprotonated bases (I, II, III); these represent one of the contributing canonical forms of each heterocyclic aminocompound. The negative polarisation of ring-nitrogen atoms, due to conjugation of the exocyclic nitrogen atom with the aromatic ring structure (with consequent protonation of a ring nitrogen in acid solution), has been postulated for several heterocyclic amine

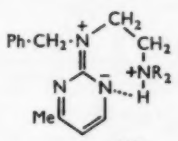
[23] Graham, *Arch. Internat. Pharmacodynam.*, 1960, **123**, 419.
[23] Staple and Wagner, *J. Org. Chem.*, 1949, **14**, 559.
[24] Albert, Goldacre, and Phillips, *J.*, 1948, 2240.
[25] Brown and Short, *J.*, 1953, 331.

systems, *e.g.*, 4-aminopyridine,[26] 4-aminoquinazoline,[27] and 2- and 4-aminopyrimidines.[23] Such polarisation will tend to stabilise the postulated hydrogen bond, which in turn stabilises the protonated base.

In the 2-aminopyrimidine derivatives, either ring-nitrogen atom may form the hydrogen bond, which will thus be formed in the most stable way. If this bond is stronger than


(I)


(II)


(III)

those formed in the 4-aminopyrimidine and 4-aminoquinazoline derivatives its effect on pK_{a_2} will be greatest, so explaining the values found. This is not unlikely in view of the probable protonation of the 4-aminoquinazolines at position 1 (see below).

Albert's explanation of the low basicity of 2-aminopyrimidine can be interpreted as an equal sharing by the ring-nitrogen atoms of the negative charge produced by conjugation of the amino-group with the ring, so that protonation is not preferred at either site. In 4-aminopyrimidine, where the extent of conjugation may be a little greater, the enhanced basicity must be due to concentration of the negative charge at one ring-nitrogen atom. If this is at position 1, then the hydrogen-bonding tendency at position 3 is smaller than in 2-aminopyrimidines. Extension of this argument to derivatives of 2-aminopyrimidine and 4-aminopyrimidine (and the similar 4-aminoquinazoline) will explain the pK_{a_2} values found.

Spectrophotometric Results and Structure.—Comparison of the absorption spectra of 4-benzylaminoquinazoline (Fig. 2), *N*-benzyl-*N′N′*-dimethyl-*N*-4-quinazolylethylenediamine (Fig. 1), *N*-benzyl-*N′N′*-dimethylethylenediamine and 4-aminoquinazoline [27] shows that in the first two the absorption at wavelengths greater than 250 mμ is due to the 4-aminoquinazoline part of the molecule.

Protonation of 4-benzylaminoquinazoline causes an increase in the intensity of the 313 mμ band and a small (2 mμ) shift to longer wavelength. The 288 mμ peak is reduced to a low-intensity shoulder at a slightly longer wavelength. There is no marked hypsochromic change to give a curve characteristic of the parent aromatic system. The changes observed are similar to those found by Steck and Ewing [26] for protonation of 2- and 4-aminopyridine and interpreted by them as being due to protonation of a ring-nitrogen atom. The spectra of *N*-benzyl-*N′N′*-dimethyl-*N*-4-quinazolylethylenediamine show that the first proton is taken up by the aliphatic amino-group and that the second causes the same kind of change as for *N*-benzylaminoquinazoline and so likewise is attached to a ring-nitrogen atom. The protonation of a ring-nitrogen atom in these compounds suggests that the postulated conjugation and resultant polarisation do occur. This view is supported by the enhanced basicity of the quinazoline nucleus when an amino-group is present in the 4-position.[24]

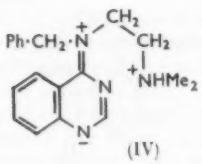
Polarisation to give structure (I) produces an *o*-quinonoid arrangement of the hetero-ring of the quinazoline nucleus while the alternative (IV) has a *p*-quinonoid structure. In the free base and monoprotonated ion the actual structure will be a hybrid of these and other canonical forms. Addition of a proton to a ring-nitrogen atom will tend to fix the structure as (I) or (IV) according to which nitrogen accepts the proton. The addition of a proton in this way increases the intensity of the long-wavelength (324 mμ) band of *N*-benzyl-*N′N′*-dimethyl-*N*-4-quinazolylethylenediamine (Fig. 1) so that this band

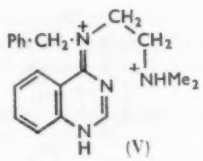
[26] Steck and Ewing, *J. Amer. Chem. Soc.*, 1948, **70**, 3397.
[27] Hearn, Morton, and Simpson, *J.*, 1951, 3318.

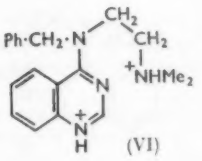
XUM

may be assigned to the quinonoid form present in the doubly charged ion The shorter-wavelength band (292 mμ) may then be assigned to the other quinonoid form.

In the free base excitation of the polar ground state will give a non-polar benzenoid structure (cf. Mason [28]). Of the two quinonoid forms the one which releases the greater strain on excitation (*i.e.*, in which the charge separation is the greater) will require the


(IV)


(V)


(VI)

less energy. This is the *para*-quinonoid form and the long-wavelength band can thus be assigned to this form. Support for this view is offered by a comparison of the two band intensities. The long-wavelength band has the greater intensity, as would be expected in view of the greater change in dipole moment which occurs on excitation of the *para*-quinonoid form. Excitation of the doubly charged ion will cause an even greater change in dipole moment (V ⟶ VI), so accounting for the increased intensity found. Thus the evidence points to protonation of position 1 of the quinazoline ring, as required for the explanation of pK_a values given above.

Structure, pK_a Values, and Anti-histamine Activity.—Compound no. 27 (Table 3) has almost the same activity as Thonzylamine and differs from it only in having a methyl group in the 4-position in the pyrimidine ring. This substituent has therefore little effect on anti-histamine activity, unlike its effect with pyridine derivatives [29] 6-Methyl-4-pyrimidyl derivatives as a group have the highest activity, 4-methyl-2-pyrimidyl the next, and the bicyclic 4-quinazolyl group the least, the last observation conforming with previous results in this field.[30] The retention of activity on altering the point of attachment of the basic side chain from the 2- to the 4-position in the pyrimidine ring is in strong contrast to the analogous change in the pyridine series.[29] It probably arises because the 4-position in the pyrimidine ring, unlike that of the pyridine ring, is a neighbour of a ring-nitrogen atom. All substituents save methyl in the 4-position of the benzyl group enhance activity, methoxyl having the greatest effect.

The pK_a values show that at physiological pH protonation occurs only at the dialkylamino-group and that the proportion of free base to salt is rather small, varying between 1% for compound no. 31 to 16% for compound no. 18. There is some indication from the pK_a values and ED_{50} values that the free base is the species active against histamine, but no further conclusions can be drawn from these results.

We thank the Chemical Society and the Pharmaceutical Society of Great Britain for grants towards the expense of this work.

THE UNIVERSITY, HULL.
THE INSTITUTE OF TECHNOLOGY, BRADFORD. [*Received, October 17th*, 1960.]

[28] Mason, *Chem. Soc. Spec. Publ.* No. 3, 1955.
[29] Adamson, *Chem. and Ind.*, 1951, 2.
[30] Chapman, James, and Williams, *J.*, 1952, 4024.

370. *The Infrared Spectra of Some Oxamides and Thio-oxamides.*

By Brian Milligan, E. Spinner, and J. M. Swan.

The infrared spectra of four substituted oxamides, three dithio-oxamides, and six monothio-oxamides [1] have been measured. The carbonyl stretching bands behave as expected for *trans*-oxamides. The thiocarbonyl stretching vibration is not localized in these compounds.

The infrared spectra of oxamide, dithio-oxamide, and their deuterated derivatives were measured, and found to be in accord with *trans*-structures, by Scott and Wagner,[2] who proposed complete vibrational assignments. The present study, of both symmetrical and unsymmetrical derivatives, enabled us to test some of their conclusions.

Experimental.—Materials were either commercially available or were prepared as before.[1]

Infrared spectra were determined with a Perkin–Elmer 21 double-beam spectrophotometer fitted with a sodium chloride prism; all materials were examined in the solid state, in potassium bromide discs (concentration, 1 in 200). The results are tabulated.

Assigned bands in the infrared spectra.[a,b]

	NHX·CO·CO·NHY				NHX·CO·CS·NHY			
X =	H	C_6H_{11}	Ph	Ph	H	C_6H_{11}	Ph	Ph
Y =	C_6H_{11}[c]	C_6H_{11}	C_6H_{11}	Ph	C_6H_{11}	C_6H_{11}	C_6H_{11}	Ph
ν(HNH)$_{as}$	3365s				3372ms			
ν(NH)	3290s	3280s	3280s	3300ms	3228s	3236ms	3252ms	3244m
	3205ms				*3200*ms		3200ms	3196mw
ν(HCH)	2914ms	2912ms	2918ms		2920ms	2920ms	2920ms	
	2846m	2842m	2845m		2846ms	2846mw	2846mw	
ν(C=O)	1691mw			*1687*mw				
	1654vs	1645s	1657s	1664s	1677s	1665s	1674s	1672s
δ(NH)$_{ip}$	1535s	**1511**s	**1511**s	**1526**, **1512** vs	**1512**vs	**1510**vs	**1527**vs, 1516s	1453s, **1517**s
HCH scissoring	1449ms	1448m	1445s	1440s	1453m	1449m	1447s	1447s
ν(C–N), ν(C=S)					*1393*ms	1396m	1390m	
					1385s	1364mw	1361mw	1374ms
					1025ms	1054ms	1038ms	1058m
						1041m	1030m	

	NHX·CS·CS·NHX			COA·CSB			*N*-Z. Morpholine	
X =	C_6H_{11}	CH_2·OH	CH_2·CO_2H	A = NHPh, B = NEt_2	NH_2	Me Morph	Z = CHS	Ac
					Morph[d]			
ν(NH)	3140ms	3260ms	3150s	3267ms	3325s			
		3165s	3050m	3080m	3180ms			
ν(HCH)	2908ms	2925mw	2925ms	2965mw	2945w	2955w	2955mw	2950w
	2840m	2866w	2865mw	2920w	2910w	2895mw	2888w	2885vw
				2855w	2840mw	2850mw	2843mw	2848m
ν(C=O)			**1715**vs	**1650**s	**1657**s	1693s		**1646**s
δ(NH)$_{ip}$	**1509**, **1503** s	1534ms	1529, 1517 s	1511s	1601m			
		1515s						
HCH scissoring	1447m	1470m	1440m	1442s	1435m	1439ms	1437m	1428ms
ν(C–N), ν(C=S)	1388ms	1386m	1400m		1513s	**1513**vs	**1509**s	
	1362m	1369mw	1367ms		1062m	1062m	1066ms	
	973ms	916ms	901, 883 ms		1028ms	1026m	1023ms	
ν(CCO)$_{as}$		1049s	1249vs					
Morph					1240, 1233 ms	1263ms	1253m	1251ms
						1233ms	1230s	
						1112s	1110s	1115ms
					1105	1003ms	1008mw	994m

[a] Complete spectra will be recorded in the D.M.S. scheme (Butterworths, London). [b] Wavenumbers in cm.$^{-1}$. Intensities: vs = very strong, s = strong, m = medium, w = weak; strongest band in bold type; inflexions in italics. *as* denotes antisymmetric stretching, *ip* in-plane bending. [c] Cyclohexyl. [d] Morpholinyl.

[1] Milligan and Swan, *J.*, 1959, 2969; *J.*, 1961, 1194.
[2] Scott and E. L. Wagner, *J. Chem. Phys.*, 1959, **30**, 465.

XUM

Discussion

C=O *Stretching Frequencies.*—A symmetrically substituted *trans*-oxamide should show a prominent infrared absorption band due to the out-of-phase carbonyl stretching motion, but none due to the in-phase carbonyl stretching; for an unsymmetrically substituted *trans*-oxamide the latter band is allowed, though only weakly. *cis*-Oxamides, by contrast, should show both bands prominently.

Actually, the oxamide spectra show only one strong band in the C=O stretching region, *viz.*, the out-of-phase stretching band, which occurs at 1645—1665 cm.$^{-1}$ (at 1656 cm.$^{-1}$ in unsubstituted oxamide [2]). Monocyclohexyloxamide, but not *N*-cyclohexyl-*N'*-phenyloxamide, also shows a clear second band at higher frequencies (1691 cm.$^{-1}$) due to the in-phase C=O stretching vibration (the Raman band due to this vibration in oxamide is found [3] near 1695 cm.$^{-1}$).

The C=O stretching frequency in the spectrum of a monothio-oxamide, found at 1665—1677 cm.$^{-1}$, is, on the average, 17 cm.$^{-1}$ higher than the out-of-phase C=O stretching frequency for the corresponding oxamide; *i.e.*, it is about the same as the mean of the two C=O stretching frequencies for the oxamide. The intensity of the carbonyl stretching band in the monothio-oxamide spectra, and in some oxamide spectra, is somewhat lower than one would expect for an amide, owing, presumably, to mutual dipole reduction,[4] arising from interaction between the C=O and the C=S group, or between the two C=O groups.

C–N *Stretching Bands.*—A moderately strong band at 1348 cm.$^{-1}$ in the spectrum of oxamide, and at 1428 cm.$^{-1}$ in that of solid dithio-oxamide (1393 cm.$^{-1}$ in solution), was attributed by Scott and Wagner [2] to out-of-phase C–N stretching. If the C–N stretching vibration in these substances is essentially localized, in derivatives the behaviour of the C–N stretching bands should follow that of the C=O stretching bands closely; *e.g.*, for the symmetrically substituted derivatives one should observe an out-of-phase C–N stretching band of substantially unchanged frequency.

Actually the (symmetrical) dithio-oxamide derivatives do show a moderately strong band in the range 1385—1400 cm.$^{-1}$ that could be the equivalent of the dithio-oxamide band found in solution at 1393 cm.$^{-1}$. Most of the monothio-oxamides show a band in the range 1360—1380 cm.$^{-1}$ that might be attributable to out-of-phase C–N stretching. However, the substituted oxamides show only a weak band (or none) near 1348 cm.$^{-1}$; the equivalent of the 1348 cm.$^{-1}$ band in unsubstituted oxamide seems to be missing in the derivatives. The latter band is presumably due to a mixed vibration that probably entails some C–N stretching. If the intrinsic C–N stretching frequency is considerably lower than 1350 cm.$^{-1}$, which is very likely, mixing between C–N stretching and NH_2 bending in oxamide, and between C–N–C stretching and other motions in the derivatives, is to be expected.

By implication, the findings for the oxamides throw doubt on assignments that assume an intrinsic C_{CS}–N stretching frequency near 1400 cm.$^{-1}$ for thio-oxamides (this value, in any case, seems very high). It is considered that C–N bond stretching is not a localized vibration in either oxamides or thio-oxamides.

C=S *Stretching Bands.*—The main purpose of the present work was to find out whether there are localized C=S stretching vibrations in thio-oxamides. Normally the "pure" C=S stretching frequency is observed in the range 1080—1230 cm.$^{-1}$, but the only thioamides which regularly show a thiocarbonyl stretching band in that range are pyridthiones and related compounds.[5] In primary thioamides no thiocarbonyl stretching band is observed, because of mixing between C=S and C–N stretching and NH_2 wagging or rocking.[6]

[3] Kahovec and J. Wagner, *Z. phys. Chem.*, 1941, *B*, **49**, 156.
[4] Smallwood and Herzfeld, *J. Amer. Chem. Soc.*, 1930, **52**, 1919; Smyth and McAlpine, *J. Chem. Phys.*, 1933, **1**, 190.
[5] Spinner, *J. Org. Chem.*, 1958, **23**, 2037; *J.*, 1960, 1237.
[6] Davies and Jones, *J.*, 1958, 955; Spinner, *Spectrochim. Acta*, 1959, **15**, 95.

XUM

In a dithio-oxamide in which the C=S stretching motion is localized there will be an out-of-phase C=S stretching vibration with a frequency 15—30 cm.$^{-1}$ lower than the intrinsic C=S stretching frequency, and an in-phase one with a correspondingly raised frequency; no infrared band due to the latter will be allowed for a symmetrically substituted *trans*-dithio-oxamide. Scott and Wagner [2] assigned the fairly strong band of unsubstituted dithio-oxamide at 832 cm.$^{-1}$ to out-of-phase C=S stretching.

In the spectra of the dithio-oxamides NHX·CS·CS·NHX obtained here, the strongest band(s) below 1300 cm.$^{-1}$ *due to the* NH·CS·CS·NH *grouping* are at 973 cm.$^{-1}$ and 874 cm.$^{-1}$ when X = cyclo-C_6H_{11}, at 916 cm.$^{-1}$ when X = CH_2·OH, and at 901 + 883 cm.$^{-1}$ when X = CH_2·CO_2H, as compared with 832 cm.$^{-1}$ when X = H. In view of its widely varying position, this band cannot reasonably be asigned to an essentially localized C=S stretching motion but has to be attributed to a composite vibration which entails some C=S stretching; its exact nature, however, seems to be intimately dependent on X. A second band likely to entail some C=S (and probably also C–N) stretching is the one located at 1385—1400 cm.$^{-1}$.

The compounds NHX·CO·CS·NHY exhibit a fairly prominent band at 1025—1060 cm.$^{-1}$ that is absent from the spectra of the compounds NHX·CO·CO·NHY. The vibration from which it arises undoubtedly entails C=S stretching, but is unlikely to be a localized C=S motion, because the band is absent for the monothio-oxamide containing a diethylamino-grouping in place of NHY. (The band seems to be characteristic of the NH·CO·CS·NH system.)

Morpholine Derivatives.—In order that the bands characteristic of the morpholinyl residue and of the *N*-thiocarbonylmorpholine system could be identified, the spectra of *N*-acetyl- and *N*-thioformyl-morpholine were determined.

We thank Mr. D. T. Light for technical assistance.

Department of Medical Chemistry, Institute of Advanced Studies,
Australian National University, Canberra. (E. S.)
Division of Protein Chemistry, Commonwealth Scientific and
Industrial Research Organization,
Melbourne, Australia. (B. M. and J. M. S.) [*Received, October 25th,* 1960.]

---

371. *Solvent-extraction of Septivalent Rhenium. Part I. Heterogeneous Equilibria in the System, Aqueous Nitric Acid–Potassium Perrhenate–Tributyl Phosphate.*

By A. S. Kertes and A. Beck.

The extraction of septivalent rhenium into tributyl phosphate from aqueous nitric acid has been investigated as a function of solvent concentration in the organic, and nitric acid concentration in the aqueous phase, the rhenium concentration being kept constant. The method of continuous variations has been applied to follow the formation of the extractable rhenium compound. The results revealed that perrhenic acid was the only extractable species. The solvent-dependencies have been found to be of the direct fourth-power. The mass-action effect and the anti-synergic interaction between nitric and perrhenic acid have been used to interpret the extraction mechanism involved. An attempt has been made to calculate the formation constant of perrhenic acid tetrasolvate.

During work in this laboratory on solute–solvent interactions in heterogeneous ternary systems containing aqueous mineral acids and tributyl phosphate,[1] an attempt has been

[1] (*a*) A. S. Kertes, *J. Inorg. Nuclear Chem.*, 1960, **12**, 377; **14**, 104; A. S. Kertes and V. Kertes, *Canad. J. Chem.*, 1960, **38**, 612; (*b*) *J. Appl. Chem.*, 1960, **10**, 287.

XUM

made to extract strong metal oxyacids. There have been relatively few attempts to investigate the extraction of metals in a high valency state, *e.g.*, those forming strong metal oxyacids of the type HMO_4, and it was hoped that distribution data on metals in the septivalent oxidation state would throw light on the behaviour of tributyl phosphate as extractant.

Most of the data [2] on the solvent-extraction of septivalent rhenium refer to determinations of rhenium(VII). It was shown that rhenium(VII) is extracted from strongly alkaline or neutral aqueous solutions by pyridine, piperidine, or ketones.[3] It is extracted from 2N-sulphuric acid by isopentyl alcohol, benzyl alcohol, hexahydronaphthalene, diethyl ketone, isobutyl methyl ketone, and tributyl phosphate, with distribution coefficients of 7, 5·8, 10·2, 3·7, 3·8, and 13·2 respectively. Tribalat [4] has also reported the extraction of perrhenic acid from highly acid solutions by ketones and alcohols. The highest distribution coefficients were obtained from sulphuric acid by using isopentyl alcohol.

Experimental

Reagents.—Commercial tributyl phosphate, from Commercial Solvents Corporation, was washed with sodium hydroxide solution and then six times with water, and the dissolved water was removed by distillation.[5] Baker's " Analysed c.p. " carbon tetrachloride was used as diluent without purification. The nitric acid solutions were prepared immediately before use from constant-boiling mixtures, thus eliminating contamination of more concentrated aqueous solutions with free nitrogen oxides. Potassium perrhenate was from Johnson, Matthey & Co. All other reagents used were of c.p. grade.

Equilibration and Phase Separation.—Portions (5 ml.) of standardized aqueous solutions containing various concentrations of nitric acid and potassium perrhenate were introduced into centrifuge tubes (10 ml. graduated in 0·1 ml.), and tributyl phosphate (5 ml.), with or without diluent, was added. The interface- and air-menisci were immediately noted. The stoppered tubes were then shaken, mechanically, equilibrium being shown to be reached in 15 min. Excellent phase separation was ensured by the use of tubes previously cleaned in sulphuric acid and one minute's centrifugation. The menisci at equilibrium were read with an accuracy of $\pm 0{\cdot}025$ ml. The average of at least three determinations, which never differed by more than 2%, was used in calculating the swelling of the organic phase due to the solubility in it of the aqueous solution. Aliquot parts of both phases were removed with a fine capillary pipette and diluted, the organic phase with a neutral water–ethanol mixture. Measurements were made at $20° \pm 2°$.

Analyses.—The acid content of the aqueous phase was determined potentiometrically in duplicate or triplicate by standard alkali, a Beckman Zeromatic pH-meter being used.

Potassium was determined in the equilibrated aqueous phase by using an EEL flame photometer. No interference was observed due to the presence of nitric acid or traces of tributyl phosphate in the solutions.

For determination of the low concentrations of nitrate ions use was made of the very sensitive reaction of nitrate with brucine.[6] To an aliquot part (5 ml.) of the nitrate solution were added a 2% brucine solution (0·5 ml.), concentrated sulphuric acid (10 ml.), and water (10 ml.). After the mixture had reached room temperature, the absorbance was measured on a Beckman model B spectrophotometer at 410 mμ. Neither perrhenate nor the ester interfered with this determination.

Perrhenate was determined only in aqueous solution, by the thiocyanate-reduction method.[7] Aliquot parts (0·5—1 ml.) were treated successively with concentrated hydrochloric acid (2 ml.), a 20% solution (0·1 ml.) of potassium thiocyanate, and 35% stannic chloride solution (0·15 ml.).

[2] Tribalat, *Compt. rend.*, 1947, **224**, 469; *Ann. Chim.* (*France*), 1949, 323; *Analyt. Chim. Acta*, 1952, **6**, 142; Miller, *J.*, 1941, 792.

[3] Gerlit, Proc. Internat. Conf. Peaceful Uses of Atomic Energy, United Nations, 1956, Vol. VII, p. 145; Goishi and Libby, *J. Amer. Chem. Soc.*, 1952, **74**, 6109.

[4] Tribalat, " Rhénium et Technetium," Gautier-Villars Publ., Paris, 1957.

[5] Peppard, Driscoll, Sironen, and McCarty, *J. Inorg. Nuclear Chem.*, 1957, **4**, 326; Kennedy and Grimley, A.E.R.E., CE/R 968.

[6] Noll, *Ind. Eng. Chem. Analyt.*, 1945, **17**, 426.

[7] Tribalat, *Analyt. Chim. Acta*, 1949, **3**, 113.

After 15 min. rhenium was extracted from the resulting solution by isopentyl alcohol, and the absorbancy of the organic layer was measured at 435 mμ on the Beckman model B spectrophotometer. Excessive quantities of nitric acid were neutralized with calculated amounts of alkali without phenolphthalein, as originally indicated, because turbidity appeared on addition of the indicator. The method being very sensitive, freshly prepared and pure reagents were required. When less than 10^{-4} mole of rhenium was determined, interference was observed due to the presence of traces of tributyl phosphate in the equilibrated aqueous solutions. In these cases the traces of phosphate were removed by a preliminary extraction with carbon tetrachloride. This additional manipulation caused the limits of accuracy of these determinations to be double the normally estimated ±3%.

Results and Discussion

Experiments were carried out with tributyl phosphate concentrations of 3·65M (undiluted), 3M, 2M, and 1·5M; the nitric acid concentration was varied between 0·1 and 8M, with a potassium perrhenate concentration of 10^{-3}M (except in the Job experiments). Preliminary experiments showed that perrhenate is not extracted in absence of nitric acid or when the concentration of this acid exceeds 8—9M, even when undiluted tributyl

Partition of rhenium(VII) *between aqueous nitric acid and tributyl phosphate.*

Initial $KReO_4$ concentration = 1×10^{-3}M.

Expt. no.	$[Bu_3PO_4]$ in CCl_4 (M)	$[HNO_3]$ (M)			$[ReO_4]$ (10^{-5}M)		$E_a°$ (ReO_4)
		Initial aq. soln. $[HNO_3]_i$	Equil. aq. phase $[HNO_3]_a$	Equil. org. phase $[HNO_3]_o$	Equil. aq. phase $[ReO_4]_a$	Equil. org. phase $[ReO_4]_o$	
1	3·65	0·105	0·083	0·024	6·17	90·5	14·7
2	3·65	0·206	0·143	0·066	3·76	92·6	24·6
3	3·65	0·514	0·308	0·209	2·02	92·5	45·8
4	3·65	1·025	0·570	0·464	1·28	93·2	73·0
5	3·65	1·344	0·726	0·623	1·88	92·2	49·0
6	3·65	1·878	1·035	0·901	7·03	85·1	12·1
7	3·65	3·813	2·245	1·620	2·07	74·8	3·60
8	3·65	5·140	3·290	1·905	44·2	53·5	1·21
9	3·65	7·735	5·225	2·718	82·0	23·6	0·290
11	3·00	0·105	0·088	0·018	37·8	61·3	1·62
12	3·00	0·206	0·162	0·048	32·0	66·6	2·08
13	3·00	0·514	0·347	0·170	18·7	79·0	4·23
14	3·00	1·025	0·646	0·398	9·30	87·5	9·40
15	3·00	1·344	0·838	0·521	10·3	86·6	8·40
16	3·00	1·878	1·170	0·730	16·6	80·2	4·83
17	3·00	3·813	2·476	1·402	44·2	55·2	1·25
18	3·00	5·140	3·487	1·750	68·2	33·8	0·495
19	3·00	7·735	5·630	2·321	93·6	12·6	0·135
21	2·00	0·105	0·097	0·009	80·7	20·6	0·260
22	2·00	0·206	0·185	0·023	63·5	36·6	0·576
23	2·00	0·514	0·426	0·092	54·3	46·0	0·848
24	2·00	1·025	0·778	0·261	34·3	65·2	1·90
25	2·00	1·344	1·008	0·378	39·3	59·9	1·52
26	2·00	1·878	1·415	0·498	57·2	42·5	0·741
27	2·00	3·813	2·780	1·118	84·4	18·6	0·220
31	1·50	0·105	0·101	0·004	90·6	6·31	0·071
32	1·50	0·206	0·198	0·009	89·1	11·4	0·127
33	1·50	0·514	0·461	0·058	81·9	19·3	0·236
34	1·50	1·025	0·866	0·171	81·1	20·1	0·248
35	1·50	1·344	1·099	0·281	76·7	24·3	0·317
36	1·50	1·878	1·535	0·377	88·4	11·6	0·131

phosphate is used. With acid concentrations less than 0·1M or greater than 4M, and concentrations of tributyl phosphate in carbon tetrachloride less than 1·5M, the partition coefficient was too low for accurate estimation. The results obtained are presented in the Table.

For study of the equilibrium between the acid and perrhenate in the aqueous phase,

XUM

Job's method of continuous variations was used.[8] The concentration of phosphate in the diluent was kept constant, at 3M, and that of total electrolytes (potassium perrhenate and nitric acid) at 0·036M. The aqueous electrolyte concentration was chosen as being almost the highest possible for aqueous solutions of potassium perrhenate. A graph of $[ReO_4]_o$, the rhenium content of the organic phase, against the molar composition of the components in the aqueous phase (Fig. 1) shows an extremum at a molar HNO_3: $KReO_4$ ratio of unity. At this ratio neither nitrate nor potassium ions were present in the organic phase. Potassium could not be detected in either of the organic phases. Nitrate appeared in the organic phase only when rhenium was not present in the aqueous phase or when the molar HNO_3: $KReO_4$ ratio was 9 : 1. The linear relation in the upward branch of the curve, and the consequent sharpness of the peak, indicate further that perrhenic acid must be the only extractable septivalent rhenium species and that the resulting perrhenic acid–phosphate solvate must have considerable stability. Perrhenate is not-extracted in absence of acid but, on the other hand, the perrhenate extraction inhibits the extraction of nitric acid when both are present in equimolar, or nearly equimolar, ratios.

The HNO_3: $KReO_4$ ratio of unity in the formation of the extractable species is confirmed by a log–log plot of $E_a°$ against nitric acid concentration in the equilibrium aqueous phase. Fig. 2 shows this plot for the different concentrations of tributyl phosphate used in this study. Independently of the phosphate content of the organic phase, the distribution ratio increases with increasing acidity in the aqueous solution up to a maximum value at about M-nitric acid in the equilibrated aqueous phase. The slope of unity of the branches showing increases indicates a HNO_3: $KReO_4$ ratio of unity, and the dependence of $E_a°$ on the hydrogen-ion concentration proves that the extracting species must be a strong acid, identified as free perrhenic acid.

The solvation number of perrhenic acid was found by the slope of a log–log plot of $E_a°$ against the concentration of tributyl phosphate in the initial organic phase at constant nitric acid concentrations. The straight lines in Fig. 3, representing this graph, show a slope of ~4 for all the acid concentrations used, suggesting that a tetrasolvate of perrhenic acid exists in the tributyl phosphate phase. Although use of arguments of this type for the determination of the solvation number may be criticised [9] when high tributyl phosphate concentrations are used, we believe that the present results are not misleading. The identical solvation number of four, recently revealed for perchloric acid, a very similar molecule to perrhenic acid, can be cited as a further argument for the existence of perrhenic acid tetrasolvate. Kertes and Kertes,[15] and Fomin and Maiorova,[10] from completely different experiments, deduced the existence of a complex $HClO_4,4(Bu_3PO_4)$ in the organic phase.

An attempt has been made to calculate the equilibrium constant of the reaction

$$4Bu_3PO_4(org.) + H^+(aq.) + ReO_4^-(aq.) \rightleftharpoons HReO_4(Bu_3PO_4)_4(org.)$$

$$K = [HReO_4(Bu_3PO_4)_4]_o/[Bu_3PO_4]_o^4[H^+]_a[ReO_4^-]_a$$

taking into account the degree of ionization of nitric acid [11] and identifying $[HReO_4(Bu_3PO_4)_4]_o$ with $[ReO_4]_o$, the concentration of rhenium in the organic phase. Free tributyl phosphate (*i.e.*, the portion not engaged in the complex) was calculated by assuming complete formation of the nitric acid monosolvate [12] HNO_3,Bu_3PO_4. The constants calculated varied between 0·55 and 0·11, with an average of 0·21. Several of the values diverge drastically from the mean value, especially at high phosphate and

[8] Cf. Irving and Pierce, *J.*, 1960, 2565; Specker, Cremer, and Jackwerth, *Angew. Chem.*, 1959, **71**, 492; Jackwerth and Specker, *Z. analyt. Chem.*, 1959, **168**, 340.
[9] Cf. Hesford and McKay, *Trans. Faraday Soc.*, 1958, **54**, 573.
[10] Fomin and Maiorova, *Zhur. neorg. Khim.*, 1960, **5**, 1100.
[11] Young, Maranville, and Smith, in "The Structure of Electrolytic Solutions," ed. W. J. Hamer, John Wiley & Sons, New York, 1959, p. 42.
[12] Tuck, *J.*, 1958, 2783; Alcock, Grimley, Healy, Kennedy, and McKay, *Trans. Faraday Soc.*, 1956, **52**, 39.

Vol. 1961, page 1924, line 7 *.
For $K = [HReO_4(Bu_3PO_4)_4]_o/[Bu_3PO_4]_o[H^+]_a[ReO_4^-]_a$
read $K = [HReO_4(Bu_3PO_4)_4]_o/[Bu_3PO_4]_o^4[H^+]_a[ReO_4^-]_a$.

XUM

low nitric acid concentrations. Fomin and Maiorova [10] reported a mean value of 0·16 for the formation constant of the perchloric acid tetrasolvate, the variation being 0·12—0·20. The value of this constant is very near to our value of 0·21 for $HReO_4,4Bu_3PO_4$.

The first main factor influencing the system under consideration is the similarity of the two extracting species HNO_3 and $HReO_4$, the distribution of which between the two phases depends on their concentration and on the degree of dissociation of the two compounds containing an ion in common. The ratio of the only extractable species (undissociated $HReO_4$ to undissociated HNO_3) in the aqueous phase should be governed by

FIG. 1. *Plot of the rhenium content of the organic phase, $[ReO_4]_o$, against the molar composition of the initial aqueous solutions in experiments of Job's method of continuous variations.*

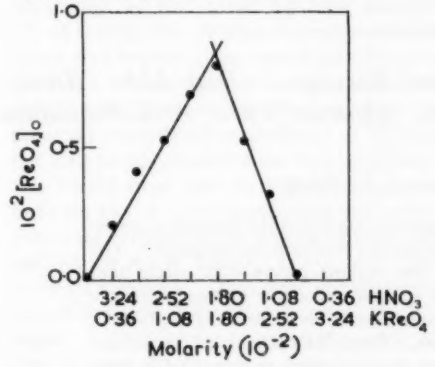
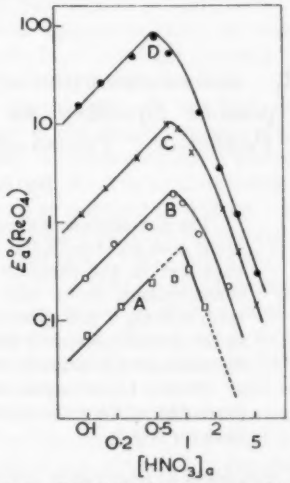


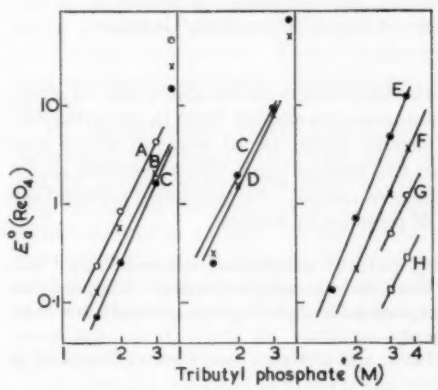
FIG. 2. Log–log *plot of the rhenium extraction ratio $E_a°(ReO_4)$ against hydrogen-ion concentration in the equilibrated aqueous phases.*



Molarity of tributyl phosphate: A, 1·5; B, 2·0; C, 3·0; D, 3·65.

FIG. 3. Log–log *plot of the rhenium extraction ratio, $E_a°(ReO_4)$, against tributyl phosphate concentration in the organic phase for various initial nitric acid concentrations.*

Molarity of nitric acid: A, 0·514; B, 0·206; C, 0·105; D, 1·344; E, 1·878; F, 3·813; G, 5·140; H, 7·735.



mass-action effect, depending on the strength of the two acids. For the time being no quantitative interpretation of the mass-action effect can be offered, but in our opinion the differences in the acid-to-extractant affinities and the difference in their solvation number are not alone sufficient to explain the extraction mechanism involved.

The increase in amount of perrhenic acid in the organic phase at low nitric acid concentration, and its decrease at higher nitric acid concentrations, may be explained roughly by the competition between the two acids for the available tributyl phosphate. One would expect the formation of higher solvates to be favoured when the concentration of tributyl phosphate is much greater than that of the extractable nitric and perrhenic acid.

XUM

The progressive uptake of nitric acid by the phosphate results in the formation of lower perrhenic acid solvates, a phenomenon consistent with previous findings in extraction equilibria.[9] It seems, therefore, that all the rhenium compounds containing less than four mol. of tributyl phosphate have a smaller tendency to remain in the organic phase than has the stable monosolvate of nitric acid,[12] thus forcing the rhenium out of the organic phase.

The authors thank Mr. H. A. C. McKay, Director of the CENTO Institute of Nuclear Science, Tehran, for his authoritative comments, also Dr. Y. Marcus, Head of the Radiochemical Laboratory, Israel Atomic Energy Commission, for helpful discussion.

Department of Inorganic and Analytical Chemistry,
Hebrew University of Jerusalem,
Jerusalem, Israel. [*Received, August 18th*, 1960.]

---

372. *Solvent-extraction of Septivalent Rhenium. Part II.*[1] *Heterogeneous Equilibria in the System, Aqueous Nitric Acid–Potassium Perrhenate–"Tri-iso-octylamine."*

By A. S. Kertes and A. Beck.

The distribution of rhenium in its highest oxidation state between aqueous nitric acid and tris-(2,2,4-trimethylpentyl)amine has been investigated. The variation in the rhenium molarity in the organic phase with nitric acid concentration shows that the rhenium species extracted is free perrhenic acid, $HReO_4$. Job's method of continuous variations indicated $NR_3,HReO_4$ as the species present in the organic phase. Some information on the similar distribution mechanisms for rhenium(VII) in this amine system and in that of Dowex-1, an anion-exchange resin, is also obtained. Evidence is presented which indicates that the affinity of the amine for ReO_4^- is higher than for NO_3^-.

The usefulness of long-chain amines of high molecular weight for the extraction of strong mineral acids [2-4] suggests that it might be advantageous to employ them in the extraction of metals in a high valency state, *i.e.*, those forming strong metal oxyacids of the type HMO_4. "Tri-iso-octylamine" was selected for the present work which involved studying the behaviour of a metal as anion rather than as cation. No previous investigations seem to have been reported on the extraction of rhenium by amines.

Experimental.—The amine, which was 92·4% pure as determined titrimetrically,[4] was obtained from Union Carbide Chemicals Co., and was used without purification. Carbon tetrachloride was of the grade used in Part I.[1] Fresh organic solvents were prepared every few days. The other reagents were of the standard reagent grade.

Equilibration techniques, experimental procedures, and analyses used were as described in Part I.

Results and Discussion

It has been shown (see, *e.g.*, ref. 3) that the heterogeneous equilibria in solvent-extraction processes with long-chain amines are by no means simple. With these two completely immiscible phases there are some "side processes" in amine–metal or amine–acid

[1] Part I, preceding paper.
[2] (*a*) Moore, *Analyt. Chem.*, 1957, **29**, 1060; Schindewolf, *Z. Elektrochem.*, 1958, **62**, 335; Bizot and Trémillon, *Bull. Soc. chim. France*, 1959, 122; (*b*) Allen, *J. Phys. Chem.*, 1956, **60**, 239, 943.
[3] Coleman, Brown, Moore, and Allen, Proc. Internat. Conf. Peaceful Uses of Atomic Energy, U.N. 1958, Vol. XXVIII, p. 278.
[4] Boirie, *Bull. Soc. chim. France*, 1958, 980, 1088; Thesis, Paris, and C.E.A. Report No. 1262, 1960.

XUM

extraction that are not general for other classes of solvents; the two chief side reactions are the formation of high polymeric aggregates of the amine salt in the organic layer [2b,3,5] and of stoicheiometrically undefined amine–nitrate compounds, the latter caused by the varying and irregular solubility of the acid in the normal amine nitrate, R_3N,HNO_3.[6,7] These factors must be taken into account as causing a variation in the extraction mechanism expected. On the other hand, the species soluble in the organic phase was not hydrated in the amine–nitrates system,[7] as determined by direct Karl Fischer analysis of the equilibrated organic layer, and this factor could be ignored.

(a) *Stoicheiometry between* $KReO_4$ *and* HNO_3 *in the Extracted Species.*—Variation in the extraction of perrhenate by the amine in carbon tetrachloride as a function of the molar $KReO_4 : HNO_3$ ratio in the initial aqueous solution was studied under three sets of conditions: (1) Job's method of continuous variations; (2) changing the nitric acid concentration in the initial aqueous solution at constant perrhenate concentration; and (3) changing the perrhenate concentration in the initial aqueous solution at constant nitric acid content; the amine concentration in the organic layer was kept constant.

Job's method (curve 1, Fig. 1) indicated a molar $KReO_4 : HNO_3$ ratio of ~1·2 : 1. Additional evidence was obtained from two series of experiments. In the first, with a constant concentration (0·024M) of potassium perrhenate in the initial aqueous solution, the nitric acid concentration was varied and, in the second, the concentration of perrhenate was varied from zero to 0·024M at a constant concentration of nitric acid of 0·024M; in both series the amine concentration in the organic layer was constant at 0·024M. Fig. 2 shows the graph of molar concentration of perrhenate in the equilibrated organic layer plotted against the molar $KReO_4 : HNO_3$ ratio (for the wide range of ratios 0·05—20) in the initial aqueous solutions. As shown, the maximum rhenium content in the organic phase appears at a $KReO_4 : HNO_3$ ratio of unity. In Fig. 3 the perrhenate molarity of the equilibrated organic layer is plotted against the nitric acid concentration in the initial aqueous solution. The straight line for initial acid concentration, up to ~0·015M, with unit slope predicts the transfer of one mole of perrhenic acid to the organic phase per mole of nitric acid in the initial aqueous solution. The departure from the unit slope at higher acid concentrations will be dealt with below. These experiments indicate that the perrhenic acid must be the only extractable septivalent rhenium species. Perrhenate is not extracted in the absence of acid.

(b) *Stoicheiometry between* $HReO_4$ *and Amine.*—In experiments by Job's method the initial nitric acid concentration was kept constant, and the initial perrhenate concentration and the amine concentration in the organic layer were varied. In the plot of these results (Fig. 4), the extremum appears at a molar $KReO_4$: Amine ratio of unity, suggesting a solvation number of one. It has recently been shown [8] that the only anionic rhenium species present in the aqueous solution for a very wide range of acid concentrations is the normal perrhenate ion, ReO_4^-, of tetrahedral symmetry, and that perrhenic acid is $HReO_4$ and not H_3ReO_5 or H_5ReO_6. It seems evident that the normal amine salt of a strong monobasic acid, such as perrhenic, must have the stoicheiometric composition of $R_3N,HReO_4$.

(c) *Relative Affinities of* $HReO_4$ *and* HNO_3 *for the Extractant.*—Of the mineral acids so far investigated,[3] perchlorate will probably have the highest affinity for the amines. The order of affinities shown in acid extraction by amines is generally similar to that shown by anion-exchange resins, namely, $ClO_4^- > NO_3^- > Cl^- > HSO_4^- > F^-$ (the order of exchange of one anion for another). If in the aqueous phase the nitric acid concentration is less than that of perrhenate, the perrhenate concentration in the equilibrated organic

[5] Allen, *J. Phys. Chem.*, 1958, **62**, 1119; *J. Amer. Chem. Soc.*, 1958, **80**, 4133; McDowell and Baes, jun., *J. Phys. Chem.*, 1958, **62**, 777; McDowell and Allen, *ibid.*, 1959, **63**, 747.
[6] Carswell and Lawrance, *J. Inorg. Nuclear Chem.*, 1959, **11**, 69.
[7] Platzner, M.Sc. Thesis, Hebrew University, 1960.
[8] Earley, Fortnum, Wojcicki, and Edwards, *J. Amer. Chem. Soc.*, 1959, **81**, 1295.

XUM

layer appears to approach a constant limiting value which depends on the nitric acid concentration; one g.-ion of H^+ in the initial aqueous solution increases the perrhenate content of the organic layer by one mole, before any nitric acid passes into the organic phase, as shown by results presented in Fig. 3. On the other hand, with an excess of nitric acid, increasing the perrhenate concentration leads to almost 100% extraction, as shown in Fig. 5. The unit slope of the curves in Figs. 3 and 5 at lower electrolyte level

FIG. 1. *Plot of* (I) $[ReO_4^-]_o$ *and* (II) $[NO_3^-]_o$ *(perrhenate and nitrate content in the organic layer) against the molar composition of the initial aqueous solutions in experiments with continuous variations (amine concentration* 0·03M).

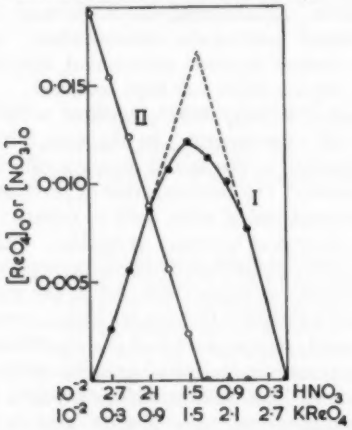


FIG. 2. *Rhenium concentration in the equilibrated organic layer plotted against the molar* $KReO_4 : HNO_3$ *ratio of the initial aqueous solution (initial amine concentration in* CCl_4 0·024M).

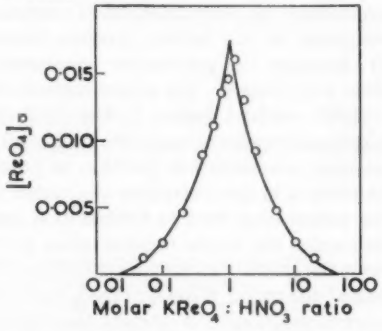


FIG. 3. *Perrhenate concentration in the equilibrated organic layer plotted against the concentration of nitric acid in the initial aqueous solution (initial aqueous* $KReO_4$ *concentration* 0·024M; *initial amine concentration in* CCl_4 0·024M).

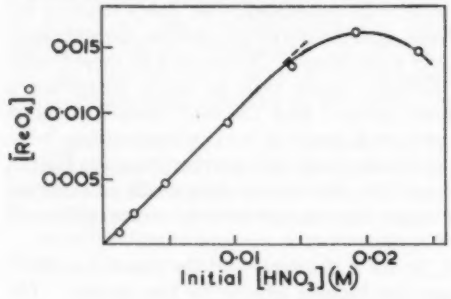
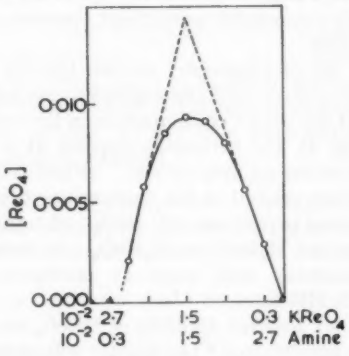


FIG. 4. *Plot of* $[ReO_4]_o$ *(perrhenate molarity in the organic layer) against the molar ratio* $KReO_4$ *: amine at constant nitric acid concentration* (0·03M) *in the initial aqueous layer.*



indicates a first-power dependence of $[ReO_4]_o$ on either the initial nitric acid or the initial perrhenate concentration when the initial aqueous solution contains an excess of nitric acid. This simple proportionality does not hold for the higher range of total electrolyte concentrations (see Figs. 3 and 5), where the latter concentration approaches the "saturation" of the amine. For the results shown in Fig. 6, the total electrolyte concentration of the aqueous layer was chosen so as not to reach the saturation region of the amine; here, for both ions, the slope of unity, up to complete extraction, shows a first-power dependence on the amine concentration in the organic phase. As the hydrogen

XUM

ions in the organic phase are due either to the nitric acid or to the perrhenic acid extracted, the differences between $[H^+]_o$ and $[NO_3^-]_o$ represent the amount of perrhenic acid extracted. The analytical results confirmed this argument: perrhenic acid is the first species passing into the amine phase from an aqueous solution containing nitric and perrhenic acid in

FIG. 5. *Perrhenate concentrations in the equilibrated organic layer plotted against its concentration in the initial aqueous solution (initial* HNO_3 *concentration* 0·024M *in the aqueous layer; initial amine concentration in* CCl_4 0·024M).

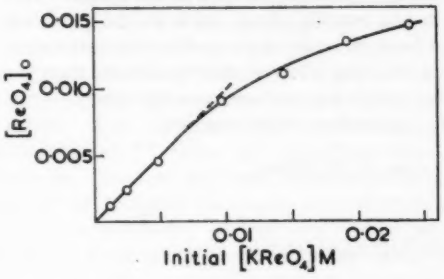


FIG. 6. *Plot of* $[H^+]_o$ *and* $[NO_3^-]_o$ *(hydrogen-ion and nitrate concentrations in the organic layer) against initial amine concentration in the organic phase at constant initial concentration of nitric acid* (0·215M) *and perrhenate* (0·024M) *in the aqueous layer.*

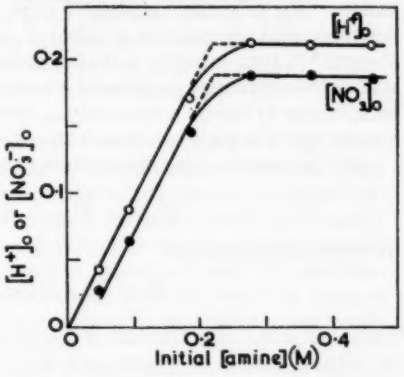
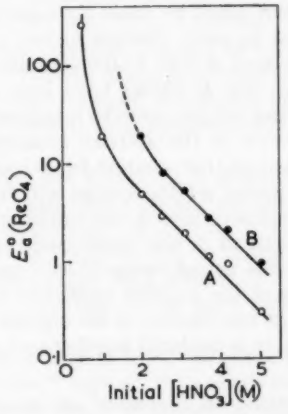


FIG. 7. *Semi-log plot of the extraction ratio of perrhenate with changing nitric acid concentration in the initial aqueous solution [initial perrhenate concentration* 0·012M *in the aqueous layer, and initial amine concentration in* CCl_4 (A) 0·23 *and* (B) 0·46M].



equimolar, or nearly equimolar, concentrations. When perrhenic acid has been completely extracted, extraction of nitric acid starts, provided enough amine is available. Further evidence for the stronger perrhenic acid–amine complex is shown in Fig. 1 where curve II represents the nitric acid concentration in the equilibrated organic layer as determined by Job's method. When the ratio $KReO_4 : HNO_3$ exceeds unity, no nitrate is found in the organic phase, and when this ratio is less than unity rhenium is almost completely extracted.

(d) *Effect of High Acid Concentration.*—To extend the concentration ranges studied, the variation of $E_a°(ReO_4)$ with higher concentrations of nitric acid was measured for constant amine concentrations. In Fig. 7, the calculated extraction ratio has been plotted against initial nitric acid concentrations. The results suggest a trend towards lower perrhenate

XUM

extraction as the concentration of nitric acid in the aqueous layer increases. Chu and Diamond [9] have found that the distribution ratio of traces of ReO_4^-, as measured on a Dowex-1 anion-exchange resin, decreased with increasing nitric acid concentration in the eluant. The general similarity of amine extraction to resin sorption of anions (compare our Fig. 7 with Fig. 4 of ref. 9) is supported by this comparison. Thus it appears that the conclusions reached for the previous tributyl phosphate system are valid also for the system now under consideration.

The effect of the concentration of the macroelectrolyte in this system should be less pronounced than in the tributyl phosphate system, principally because of the different solvation numbers of perrhenic and nitric acid extracted by tributyl phosphate and by the amine. The solvation number of nitric acid is unity in both systems, in contrast to the perrhenic acid tetrasolvate in tributyl phosphate and the monosolvate in the amine. It is obvious [1,10] that a highly solvated complex in the organic phase, such as the perrhenic acid–tetrakis(tributyl phosphate) solvate, must be more easily destroyed by the extraction-competition of the macroelectrolyte, nitric acid, forming a lower (mono) solvate, than is a solvate which is itself a monosolvate, such as our perrhenic acid–amine compound.

(e) *Calculation of the Equilibrium Constant.* According to the reaction

$$R_3N_o + H^+_a + ReO_{4a}^- \longrightarrow [R_3N,HReO_4]_o$$

the equilibrium constant

$$K = [R_3N,HReO_4]_o/[H^+]_a[ReO_4^-]_a[R_3N]_o$$

was calculated. The fraction of the initial free amine concentration (*i.e.*, that not engaged as nitrate–amine or perrhenate–amine complex) is taken as $[R_3N]_o$. The ratio $[R_3N,HReO_4]_o/[ReO_4^-]_a$ represents the gross extraction ratio of perrhenic acid. No calculations could be made for experiments carried out with nitric acid concentration in the initial aqueous solution so low or so high as to preclude formation of extractable perrhenic acid or lead to the saturation of the extractant, respectively. With the above limitation, the K values have been calculated and found to be about 1×10^5. The divergencies are due more to inaccuracies in the measurements than to the non-ideality of the solutions in the activity relation assumed. The calculations were made with the assumption of true solution behaviour and unit activity coefficients for the carbon tetrachloride–amine soluble species and free amine. With reasonable assumptions as to the appropriate activities in the equilibrated aqueous phase, and by neglecting the solubility of the amine in it, the values could probably be somewhat corrected, in spite of the fact that, for the actual range of acid concentrations in the equilibrated aqueous layer, the deviation of the activity coefficient from unity must be negligibly small. However, in view of the non-ideality of the organic phase in all cases where the amine molarity is greater than 0·01, it is doubtful whether such corrections would change the results to a significant extent.

Department of Inorganic and Analytical Chemistry,
The Hebrew University of Jerusalem,
Jerusalem, Israel.

[*Received, August 18th,* 1960.]

[9] Chu and Diamond, *J. Phys. Chem.*, 1959, **63**, 2021.
[10] Hesford and McKay, *Trans. Faraday Soc.*, 1958, **54**, 573.

373. *Cyclic Organic Boron Compounds. Part V.*[1] *Infrared Spectra of Borazoles and Boroxoles.*

By D. W. Aubrey, M. F. Lappert, and H. Pyszora.

The infrared spectra of eleven borazoles and twenty boroxoles, having various substituents, have been recorded and assignments have been proposed. The BN and BO ring stretching vibrations fall at ~1450 and ~1350 cm.$^{-1}$ for the two classes respectively, but these are of relatively little use for diagnosis owing to close correspondence to values of B–N and B–O stretching frequencies in appropriate acyclic compounds. However, medium-to-strong absorption near 720 cm.$^{-1}$ appears to be characteristic for both classes when substituents on the boron atoms can conjugate with the ring and this absorption is assigned to one of the out-of-plane ring vibrations. The effects of structure on group frequency shifts are considered, as is hyperconjugation in alkylboronic anhydrides.

Spectroscopic information on a number of borazoles [2-6] and boroxoles [6-9] has been reported. For borazole itself the fundamental infrared and Raman frequencies have been assigned; [2,3] these data have been extended to certain substitution derivatives (see Table 7). Interest has been either theoretical (comparison with benzenoid compounds, calculation of force constants and of distribution of potential energy among various internal co-ordinates) or analytical. The present paper is concerned with the identification and assignment of characteristic group frequencies and with the effect on these of structural factors. For this purpose we examined the spectra of many of these compounds and have brought together published information on others.

The band most frequently regarded as characteristic of the borazoles has been that at about 1450 cm.$^{-1}$ due to the ring B–N stretching frequency and recognised by its high intensity. For two compounds, $(Et{\cdot}NH{\cdot}B{\cdot}NEt)_3$ and $(Bu^nO{\cdot}B{\cdot}NEt)_3$, attention has also been drawn to a medium-intensity doublet in the 720 cm.$^{-1}$ region, assigned to the out-of-plane vibrations of the $N_3B_3N_3$ or $O_3B_3N_3$ skeletons.[4] From the disclosure [10] that borazens [$B(NR_2)_3$, $B(NHR)_3$, $B(NRAr)_3$, and $B(NHAr)_3$] have the strongest absorption at about 1450 cm.$^{-1}$ (due to the B–N asymmetric stretching vibration), it is apparent that strong absorption in that region is not diagnostic for borazoles.

Spectra of boroxoles have received scant attention. The Raman lines of the methyl- (also infrared spectrum [5]), methoxy-, dimethylamino-, and chloro-derivatives have been recorded,[6] and for certain alkoxyboroxoles [*i.e.*, metaborates, $(RO{\cdot}BO)_3$] a medium-intensity doublet in the infrared spectra at about 720 cm.$^{-1}$ appeared to be characteristic and was tentatively assigned to the out-of-plane vibration of the B_3O_6 skeleton.[7] In some aryl derivatives [*e.g.*, boronic anhydrides, $(Ar{\cdot}BO)_3$], absorption in the same region was noticed.[9]

B-*Aminoborazoles*, $(R{\cdot}NH{\cdot}B{\cdot}NR)_3$.—In general, the spectra of these compounds show: (i) several strong absorption bands in the 1600—1100 cm.$^{-1}$ region; (ii) a sharp medium-intensity band at 3400—3450 cm.$^{-1}$, undoubtedly due to the N–H stretching vibration; and (iii) a characteristic band at 715 cm.$^{-1}$, in some cases resolved into a doublet.

[1] Part IV, Aubrey and Lappert, *J.*, 1959, 2927.
[2] Crawford and Edsall, *J. Chem. Phys.*, 1939, **7**, 223.
[3] Price, Fraser, Robinson, and Longuet-Higgins, *Discuss. Faraday Soc.*, 1950, **9**, 131.
[4] Lappert, *Proc. Chem. Soc.*, 1959, 59.
[5] (*a*) Spurr and Chang, *J. Chem. Phys.*, 1951, **19**, 518; (*b*) Becher and Frick, *Z. anorg. Chem.*, 1958, **295**, 83; (*c*) Bradley, Ryschkewitsch, and Sisler, *J. Amer. Chem. Soc.*, 1959, **81**, 2635; (*d*) Watanabe, Narisada, Nakagawa, and Kubo, *Spectrochim. Acta*, 1960, **16**, 78.
[6] Goubeau and Keller, *Z. anorg. Chem.*, 1953, **272**, 303.
[7] Lappert, *J.*, 1958, 2790.
[8] Goubeau and Hummel, *Z. phys. Chem.* (*Frankfurt*), 1957, **69**, 77.
[9] (*a*) Snyder, Konecky, and Lennarz, *J. Amer. Chem. Soc.*, 1958, **80**, 3611; (*b*) Santucci and Gilman, *J. Amer. Chem. Soc.*, 1958, **80**, 193.
[10] Aubrey, Lappert, and Pyszora, *J.*, 1960, 5239.

XUM

Complexity in region (i) arises from the presence of, *inter alia*, BN and CN stretching and of CH, CH_2, CH_3, and NH deformation modes. In the methyl derivative, the strong absorption due to the methyl group makes assignment of a BN stretching frequency on relative-intensity grounds difficult, but in the higher homologues a band of outstanding intensity is clearly distinguished and may be allocated to the BN stretching mode, probably being a mixed vibration of cyclic and exocyclic modes.

The NH stretching frequencies are of the same order as in corresponding borazens, $B(NHR)_3$ in which they fall at 3420 ± 20 cm.$^{-1}$ for R = alkyl or benzyl, and 3390 cm.$^{-1}$ for R = phenyl,[10] and both sets are appreciably higher in frequency and in intensity than for amines. As for borazens, the explanation must be that there is double-bond character in the BN bonds and, as the values for borazoles and borazens are so similar, there seems no indication that double bonding in borazoles is more extensive, although appreciable aromatic character would be expected to be shown by this ring. Details are in Table 1.

TABLE 1. *Infrared bands (cm.$^{-1}$) of* B-*aminoborazoles*, $(R{\cdot}NH{\cdot}B{\cdot}NR)_3$.

R	Me	Et	Pr^i	Bu^n	Bu^s	Bu^t	Ph·CH_2	Ph
νN–H	3425	3436	3425	3436	3436	3425	3448	3425
νB–N	1513(?)	1493	1488	1493	1488	1493	1449	1497
Ring deformn. ω_{10} *	790	800	~781	787	775	790	796	782
Ring deformn. ω_6 and ω_7 *	713	717	709	709	709	—		757,† 738
	704	710						699, 693

* See text. † Includes aromatic vibrations.

In the 720 cm.$^{-1}$ region, in those cases where the absorption was resolved into a doublet, the higher-frequency band was a shoulder on that at lower frequency; in the other cases the absorption was broad.

The spectrum of the ethyl homologue was recorded, not only for a pure liquid sample (Table 4 and Fig. 1), but also for solutions of varying dilutions in carbon tetrachloride; no solvent effects were detected, suggesting only weak or no intermolecular association.

B-*Alkoxyborazoles*, $(RO{\cdot}B{\cdot}N{\cdot}R')_3$.—We have investigated only one member of this class, $(Bu^nO{\cdot}B{\cdot}NEt)_3$. This shows four particularly intense bands: at 1436 (νBN), 1379 (doublet) (CH_3 deformation), 1280 (νBO), and 1170 cm.$^{-1}$ (νCO). There is medium-intensity absorption at 728 cm.$^{-1}$. The value assigned to the BO stretching vibration compares with one at 1269 cm.$^{-1}$ for monoalkoxyborazens,[10] and both values are significantly lower than for trialkyl borates;[11] this has been discussed for borazens, in terms of more powerful back-donation from nitrogen to boron than to oxygen.[10]

The spectra of seven *B*-alkoxyborazoles have been recorded by Bradley, Ryschkevitsch, and Sisler,[5] and assignments for absorptions down to 1136 cm.$^{-1}$ were made. The BO stretching vibration (although referred to as a bending mode) was found at 1318—1330 cm.$^{-1}$ and the CO band at 1136—1157 cm.$^{-1}$. In the 1400—1450 cm.$^{-1}$ region, a medium-to-strong absorption band at ~1445 cm.$^{-1}$ was noted and also a very strong one at 1428 cm.$^{-1}$. The former was assigned to the BN stretching vibration and the latter to a methylene deformation. On intensity grounds, we prefer reversal of these assignments and we regard it as important that absorption at 715 cm.$^{-1}$ was also observed. A second BN mode at 1183 cm.$^{-1}$ was reported, which we do not find.

Boroxoles.—(i) *Introduction.* The compounds examined comprised eleven alkyl and phenyl metaborates, $(RO{\cdot}BO)_3$, five alkyl- and phenyl-boronic anhydrides, $(R{\cdot}BO)_3$, and two aminoboroxoles, $(Me{\cdot}NH{\cdot}B{\cdot}O)_3$ and $(Me_2N{\cdot}B{\cdot}O)_3$. With the simplest of these, methylboronic anhydride, it should be possible to assign all the fundamentals, partly because the geometry is established from an electron-diffraction study,[12] and also because the Raman spectrum is available.[6] Boronic anhydride and metaborate molecules, having D_{3h} symmetry (substituents considered as point masses), should have 14 skeletal vibrations. These

[11] Werner and O'Brien, *Austral. J. Chem.*, 1955, **8**, 355.
[11] Bauer and Beach, *J. Amer. Chem. Soc.*, 1941, **63**, 1394.

modes divided themselves into 5 symmetry classes: $3A_1'$; $2A_2'$; $2A_2''$; $5E'$ and $2E''$; of which vibrations belonging to A_2'' and E' should be observed in the recorded infrared spectra (E' are also Raman-active).

The two A_2'' vibrations may be approximately described as out-of-plane side-chain bending and ring bending modes, and these have been found by Goubeau and Hummel[8] for methylboronic anhydride at 570 (ω_6) and 459 cm.$^{-1}$ (ω_7); for the other boronic anhydrides investigated these vibration frequencies fall outside the range recorded.

Corresponding modes have, however, been located much higher for 1,3,5-trisubstituted benzenes and melamine,[13] and the medium-to-strong absorption band observed for metaborates[7] in the 720 cm.$^{-1}$ region undoubtedly belongs to this symmetry class. The constancy in absorption frequency in the series Me, Et, Pr^n, Pr^i, Bu^n, Bu^i, and Bu^s, favours the assignment of this band to the out-of-plane ring bending mode, but a small separation of these two modes (in melamine 30 cm.$^{-1}$) or even an overlap of absorption bands cannot be ruled out. It is possible that the shoulder observed on the high-frequency side of the main band at ~720 cm.$^{-1}$ represents the other out-of-plane deformation mode.

The five E' vibrations consist of two ring stretching and one side-chain stretching mode, one ring bending, and one side-chain bending mode. Only the first three would be expected to fall in the 5000—650 cm.$^{-1}$ region and these have been found[8] for methylboronic anhydride at 1384 (ω_8), 1226 (ω_9), and 783 cm.$^{-1}$ (ω_{10}), respectively.

The ω_8 (ring stretching) mode is found for boronic anhydrides and metaborates in the narrow range 1387—1335 cm.$^{-1}$ as the strongest band in the spectrum and is undoubtedly a B–O ring vibration, being in the same range as the B–O asymmetric stretching vibrations of trialkyl orthoborates.[11]

The ω_9 mode, which can be described approximately as a B–C stretching mode, is found at ~1200 cm.$^{-1}$ which is ~100 cm.$^{-1}$ higher than the corresponding absorption of trialkylborons.[14] Similar increases in frequency due to side-chain stretching modes have been observed for mesitylene (C–C) and melamine (C–N).[13]

The ring vibration ω_{10}, observed[8] in methylboronic anhydride at 783 cm.$^{-1}$, appears in all spectra of anhydrides and metaborates as a weak-to-medium intensity band in the 825—760 cm.$^{-1}$ region.

However, for a complete and reliable treatment of boronic anhydride and metaborate molecules more information is required than at present available and the results to date must of necessity be interpreted on a semi-empirical basis.

TABLE 2. *Infrared bands (cm.$^{-1}$) for boronic anhydrides,* $(R\cdot BO)_3$.*

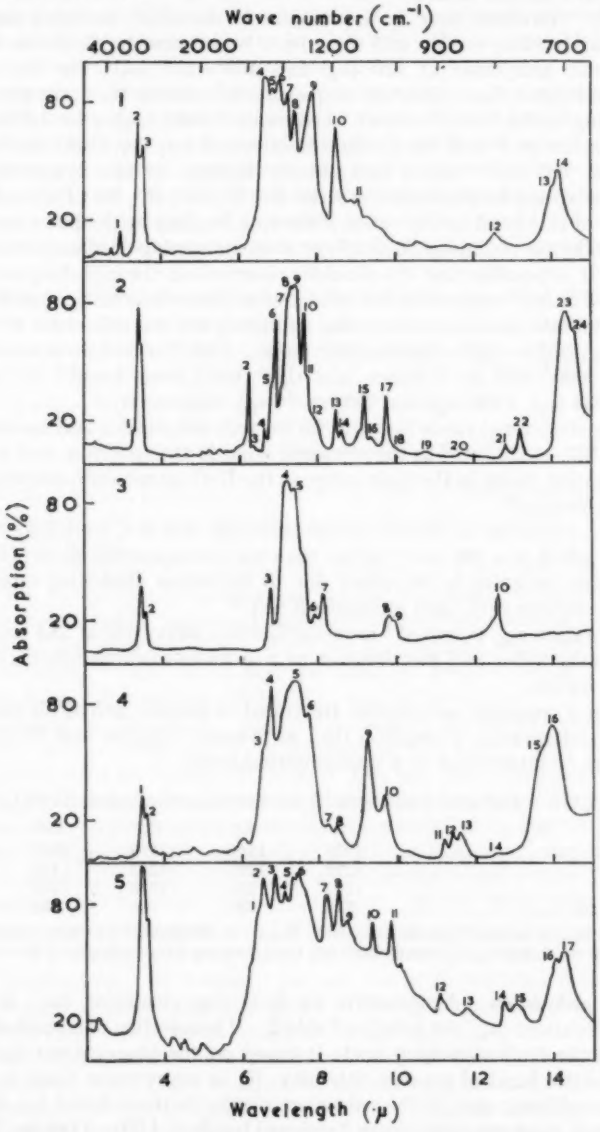
R	Me	Et	Bu^n	Bu^t	Ph
^{11}B–O (ω_8)	1370	1380	1387	1357	1451
^{10}B–C (ω_9)	1222	1225	1202	1147	1104 †
^{11}B–C (ω_9)	1253	1265	1236	1160	1087 †
Ring deformn. (ω_{10})	783	798	798	760	778

* The spectrum of isobutylboronic anhydride in carbon disulphide was also examined, but only in the 1250—650 cm.$^{-1}$ region. † Assignment not certain owing to complexity of aromatic absorptions in this region.

(ii) *Boronic anhydrides.* Assignments for B–O ring stretching (ω_8), B–C stretching (ω_9), and ring vibrations (ω_{10}) are listed in Table 2. The selection of a band at ~1370 cm.$^{-1}$ as arising from the B–O stretching mode is based on the observations that (*a*) in each spectrum this is the band of greatest intensity, (*b*) in many cases there is indication of ^{10}B/^{11}B isotopic splitting, and (*c*) the values are similar to those found for orthoborates.[11] On the other hand, Santucci and Gilman[9] assigned bands at 1170—1198 cm.$^{-1}$ in spectra of arylboronic anhydrides to the B–O stretching mode; we regard these as arising from aromatic CH deformation modes [see Table 5 and Fig. 2 for $(Ph\cdot BO)_3$]. The separation of the presumed ^{11}BC and ^{10}BC bands and also their relative intensities [see Table 6 and Fig. 3 for $(Et\cdot BO)_3$] are consistent with the interpretation and their location is in the same

[13] Jones and Orville-Thomas, *Trans. Faraday Soc.*, 1959, **55**, 203.

Infrared spectra of (1) *tris*-B-*ethylaminoborazole* (*see Table* 4), (2) *tri*-B-*phenylboroxole* (*phenylboronic anhydride*) (*see Table* 5), (3) *tri*-B-*ethylboroxole* (*ethylboronic anhydride*) (*see Table* 6), (4) *tri*-B-*methoxyboroxole* (*methyl metaborate*) (*see Table* 6), *and* (5) *tris*-B-*dimethylaminoboroxole* (*see Table* 4).



region as the ^{11}BC asymmetric stretching frequency for trimethylboron (1150 cm.$^{-1}$).[14] In the phenylboronic anhydride spectrum, unequivocal assignment for the BC stretching frequency is not easily made, because of the predominance of aromatic vibrations in the relevant (1000—1300 cm.$^{-1}$) region; however, for a series of arylboronic anhydrides an

[14] Lehmann, Wilson, and Shapiro, *J. Chem. Phys.*, 1958, **28**, 777.

absorption band in the range 1080—1110 cm.$^{-1}$ has been put forward as characterising the BC stretching mode (Santucci *et al.*[9]).

Snyder, Konecky, and Lennarz [9] regarded a band at ~700 cm.$^{-1}$ in the spectra of arylboronic acids as characteristic of these compounds (for phenylboronic anhydride, a

TABLE 3. *Infrared bands (cm.$^{-1}$) of metaborates,* $(RO\cdot BO)_3$.

R	Me	Et	Pr^n	Pr^i	Bu^n	Bu^i	Bu^s	Bu^t	Ph	Cl·CH$_2$·CH$_2$	CH$_2$Bu^i	C$_6$H$_{13}$·CHMe
νB–O	1351	1341	1355	1335	1345	1353	1337	1370	1378	1350	1342	1342
δCH(O·B<)	1427	1433	1427	1406	1427	1429	1409	—	—	1441	1425	1416
νC–O	1085	1080	1083	1119	1088	1083	1129	1182	1225	1092	1087	1082
Ring deformn. (ω_{10})	799	804	870(?)	789	810	823	822	—	789	812	?	820
Ring deformn. (ω_8)	718	722	722	723	723	724	724	—	700	715	733	735
(ω_7)	736	736	734	733	734	736	735		715	709	722	725

TABLE 4. *Frequencies and assignments of absorption bands (cm.$^{-1}$) in* (A) $(Et\cdot NH\cdot B\cdot NEt)_3$ *and* (B) $(Me_2N\cdot BO)_3$.

Frequency [a] A		Frequency [a] B		Assignment
3436	(1)			N–H stretch
2932	(2)			C–H stretch
2857	(3)			
		1575	(1)	B–N stretch (CH_3 bending) [b]
		1534	(2)	
1493	(4)			Ring stretch (ω_9)
		1456	(3)	CH_3 deformation (B–N stretch) [b]
1452	(5)			CH_3 and CH_2 deformation
1417	(6)	1412	(4)	
1376	(7)	1384	(5)	
		1342	(6)	Ring stretch (ω_8)
1342	(8)			?
1269	(9)	1224	(7)	CH_3 wagging
1180	(10)			CH_3 wagging
		1180	(8)	NC_3 stretch
		1149	(9)	CH_3 wagging
1104	(11)			C–N stretch
		1074	(10)	
		1017	(11)	
		903	(12)	
		847	(13)	
800	(12)	787	(14)	Ring deformn. (ω_{10})
		767	(15)	
717	(13)	714	(16)	Ring out-of-plane deformn. (ω_8) and (ω_7)
710	(14)	703	(17)	

[a] Numbers in parentheses refer to (A) Fig. 1 and (B) Fig. 5. [b] In the text alternative assignments are discussed.

TABLE 5. *Frequencies (cm.$^{-1}$) and assignments of absorption bands in phenylboronic anhydride.*

Frequency [a]		Assignment [b]	Frequency [a]		Assignment [b]	Frequency [a]		Assignment [b]
3031	(1)	C–H stretch (A_1)	1312	(10)	C–C stretch (B_1)	1000	(18)	Ring deformn. (A_1)
1605	(2)	C–C stretch (A_1)	1295	(11)	C–H deformn. (B_2)	927	(19)	C–H deformn. (B_2)
1575	(3)	C–C stretch (B_1)	1264	(12)	?	855	(20)	C–H deformn. (A_2)
1490	(4)	C–C stretch (A_1)	1182	(13)	C–H deformn. (A_1)	778	(21)	Ring deformn. (boroxole) (ω_{10})
1458	(5)	C–H deformn. [c]	1163	(14)	C–H deformn. (B_1)			
1447	(6)	C–C stretch (B_1)	1104	(15)	B–C stretch (ω_9)?	761	(22)	C–H deformn. (B_2)
1387	(7)	?	1087			698	(23)	Ring deformn. (B_2)
1370	(8)	Ring vibration (boroxole) (ω_8)	1064	(16)	C–H deformn. (B_2)	670	(24)	Ring out-of-plane deformn. (boroxole)
1351	(9)		1026	(17)	C–H deformn. (A_1)			

[a] Numbers in parentheses refer to Fig. 2. [b] Aromatic vibrations are designated A_1, A_2, B_1, or B_2, as appropriate (cf. Whiffen, *J.*, 1956, 1350). [c] Absorption due wholly, or in part, to liquid paraffin.

shoulder at 690 cm.$^{-1}$); however, for the aliphatic compounds we notice no absorption in this region, although we confirm the observation with phenylboronic anhydride (see Table 5 and Fig. 2).

Hennion, McCusker, Ashby, and Rutkowski [15] observed that reaction of t-butylmagnesium chloride with boron halides affords, instead of tri-t-butylboron, substantial amounts of isobutyl derivatives. It was of interest to see whether reaction with a trialkyl

[15] Hennion, McCusker, Ashby, and Rutkowski, *J. Amer. Chem. Soc.*, 1957, **79**, 5190; Hennion, McCusker, and Rutkowski, *ibid.*, 1958, **80**, 617.

XUM

borate [where only one alkoxy-group is replaced to give $Bu{\cdot}B(OH)_2$, and from this the anhydride $(Bu{\cdot}BO)_3$] led to rearrangement or not. The infrared spectrum of the product showed that it was t-butyl- and not isobutyl-boronic anhydride. The evidence is principally that the product showed no absorption between 850 and 760 cm.$^{-1}$, whereas isobutylboronic anhydride had a strong band at 830 cm.$^{-1}$. The ν_4 skeletal vibration of the t-butyl group falls at 415 cm.$^{-1}$ and that of the isopropyl group at 840—793 cm.$^{-1}$ for hydrocarbons.[16] A further notable difference between the two compounds was the presence of medium-intensity bands at 1101 and 1058 cm.$^{-1}$ in the spectrum of isobutylboronic anhydride. Two other absorptions might appear to offer scope for distinguishing the isomers: the ν_2 and ν_3 skeletal vibrations at 1140—1250 cm.$^{-1}$ and the CH deformations at 1350—1400 cm.$^{-1}$ (these values having been observed in hydrocarbons).[16] However, as these fall in regions of other strong bands, the evidence would be less decisive. The infrared spectroscopic technique, therefore, offers a method, alternative to that of nuclear magnetic resonance,[17] for distinguishing compounds having iso- from those having t-butyl groups attached to a boron atom.

(iii) *Metaborates.* In the spectrum of methyl metaborate (Table 6 and Fig. 4), the strongest bands appear at 1351vs, 1486 (shoulder at ~1520), 1427 (shoulders), 1085, and 718 cm.$^{-1}$ (shoulder at ~736 cm.$^{-1}$). On intensity grounds, and because of the close correspondence to the B–O stretching frequency in orthoborates,[11] that at 1351 cm.$^{-1}$ must be assigned to the B–O stretching frequency; it does not seem possible to distinguish cyclic and exocyclic B–O bond stretching vibrations. Bands at ~1486 and 1427 cm.$^{-1}$ (the latter with a shoulder at slightly higher frequency) are present for all other metaborates investigated, except the t-butyl and phenyl compounds (for the latter there is a medium-intensity band associated with νC:C). It is probable, therefore, that these are characteristic of CH or CH_2 deformation modes, with lower values than usual for such groups,[16]

TABLE 6. *Frequencies (cm.$^{-1}$) and assignments of absorption bands in* (A) $(MeO{\cdot}BO)_3$ *and* (B) $(Et{\cdot}BO)_3$.

Frequency [a] A		Frequency [a] B [b]		Assignment
2907	(1)	2941	(1)	C–H stretch
2841	(2)	2870	(2)	
1520	(3)	1471	(3)	C–H deformn.
1486	(4)	1404	(4)	
1351	(5)	1380	(5)	Ring stretch (ω_3)
1304	(6)			
		1265	(6)	B–C stretch (ω_9)
		1225	(7)	
1221	(7)			
1186	(8)			CH_3 wagging
1085	(9)			C–O stretch
1037	(10)	1037	(8)	CH_3 wagging (?)
		1003	(9)	C–C stretch (?)
898	(11)			
879	(12)			
863	(13)			
799	(14)	798	(10)	Ring deformn. (ω_{10})
736	(15)			Ring out-of-plane deformn. (ω_6) and (ω_7)
718	(16)			

[a] Numbers in parentheses refer to (B) Fig. 3 and (A) Fig. 4. [b] Gas-phase spectrum.

because they are adjacent to an oxygen atom attached to the highly electronegative boron atom. This view is supported by observations on orthoborates, where similar absorptions have been recorded.[11] Relevant data are summarised in Table 3.

The narrow range (43 cm.$^{-1}$) over which the B–O stretching frequency falls and the wider spread (150 cm.$^{-1}$) of the C–O bands is closely paralleled in the orthoborates.[11] The infrared spectrum of tri-t-butyl borate, $B(OBu^t)_3$, has not previously been described; strong bands at 1349 and 1185 cm.$^{-1}$ can confidently be assigned to the asymmetric B–O and C–O stretching vibrations, respectively. Consequently, as for the orthoborates so for the metaborates, the values of both of these frequencies are higher for the phenyl and t-butyl compounds than for any others of those studied. This is consistent with there being a higher degree of double-bond character in the B–O bonds when there is the

[16] Sheppard and Simpson, *Quart. Rev.*, 1953, **7**, 19.
[17] Davies, Hare, and White, *J.*, 1960, 1040.

possibility of inductive or conjugative electron release. The large increases in the C–O stretching frequencies on proceeding from primary (1082 ± 3 cm.$^{-1}$) to secondary (1124 ± 5 cm.$^{-1}$) and tertiary (1182 cm.$^{-1}$) alkyl derivatives correspond to observations on the effect of branching on similar vibrations in alcohols.[18]

In the 720 cm.$^{-1}$ region, the band at higher frequency was a shoulder of the other; there is thus close resemblance to the situation with *B*-aminoborazoles.

(iv) B-*Aminoboroxoles*. The spectra of the compounds [$(Me_2N{\cdot}BO)_3$ and $(MeNH{\cdot}BO)_3$] showed strong absorption bands in the range 1540—1000 cm.$^{-1}$ and also at 702 ± 3 cm.$^{-1}$. In order to make assignments in the higher-frequency region, the spectra were compared with those of corresponding borazens[10] [$B(NHMe)_3$ and $B(NMe_2)_3$]. For the latter, bands at 1509, 1413, and 1384 cm.$^{-1}$ were assigned to deformation modes of the methyl groups, leaving others at 1449 (^{11}B) and 1471 cm.$^{-1}$ (^{10}B, weaker) as asymmetric B–N stretching vibrations. By analogy, we allocate bands in trisdimethylaminoboroxole (see Table 4 and Fig. 5) at 1456 (BN) and 1342 cm.$^{-1}$ (BO), leaving others at 1534, 1412, and 1384 cm.$^{-1}$ as CH_3 deformations. Similarly, in the spectrum of trismethylaminoboroxole, bands at 1468 and 1351 cm.$^{-1}$ are assigned to BN and BO stretching frequencies, respectively. However, assignment of a band as the B–N stretching frequency must be speculative and it is possible that for the former compound it is the 1534 cm.$^{-1}$ band.

Hyperconjugation in Alkylboronic Anhydrides.—It has been suggested[19] that trimethylboron, unlike the other Group IIIB alkyls, is monomeric because of hyperconjugative stabilisation, *i.e.*, because of contributing canonical structures of the type $Me_2\bar{B}{=}CH_2\ H^+$. Although there has recently been some doubt (see, *e.g.*, ref. 20) regarding the validity of the theory of hyperconjugation, we thought that examination of B–C stretching frequencies in the α-methyl series (*i.e.*, Me, Et, Pr^i, and Bu^t) of alkylboronic anhydrides might throw some light on the problem. The boronic anhydrides, rather than the trialkylborons, were chosen because among the latter isomerisation of the more highly branched homologues takes place,[15] presumably owing to steric strain. Hyperconjugation would imply decreased bond-shortening in the series Me > Et > Pr^i > Bu^t and this should be reflected in the B–C stretching frequencies. Although we have no information on isopropylboronic anhydride, the results in Table 2 appear to support hyperconjugation. However, the shift from the methyl to the t-butyl compound is so large that it may alternatively or additionally be due to lengthening of the Bu^t–B bond, due to steric strain.

A further observation, although not providing an unambiguous answer, is that t-butylboronic anhydride is much more readily oxidised than the n-butyl isomer. It has been assumed[21] that oxidation of trialkylborons proceeds by co-ordination of molecular oxygen with the boron atom and a subsequent 1,3-shift of alkyl from boron to oxygen to form an alkylperoxyboron compound. If attack by oxygen is rate-determining, then, if hyperconjugative effects are excluded, the n-butyl derivative should be the more labile, both on steric grounds and from considerations of inductive effects (Bu^t > Bu^n). The alternative explanation, however, is that the alkyl migration is rate-determining.

Characteristic Ring Vibrations.—In Table 7 are collected data on ring stretching [and ring out-of-plane deformation modes (in parentheses)] vibrations of borazoles and boroxoles: where no parenthetical observation is made, published results are incomplete. Frequencies are quoted in cm.$^{-1}$ and mean values are shown, unless there are wide discrepancies between different publications.

It seems that the presence of the out-of-plane ring vibrations near 720 cm.$^{-1}$ is characteristic for those borazoles and boroxoles, where the substituents on the boron atoms (RO, ArO, R_2N, RNH, Cl, Ar) can conjugate with the ring; the exceptions are t-butoxy- and t-butylamino-groups and the anomaly may be due to a steric effect.

[18] Colthup, *J. Opt. Soc. Amer.*, 1950, **40**, 397.
[19] Mulliken, *Chem. Rev.*, 1947, **41**, 207.
[20] Dewar and Schmeising, *Tetrahedron*, 1959, **5**, 160.
[21] Abraham and Davies, *Chem. and Ind.*, 1957, 1622; *J.*, 1959 429.

XUM

TABLE 7. *Ring vibrations (cm.$^{-1}$) for borazoles and boroxoles.**

X in $(X\cdot B\cdot NR)_3$	X in $(X\cdot BO)_3$	X in $(X\cdot B\cdot NH)_3$
Ph, 1405 [22]	RO, 1345 (735, 722) [7, a]	H, 1465 (<650) [2, 3, 5a]
Cl, 1392, [5b, 5d, a] 1440 [5d]	Bu^tO, 1370 (below 650) [a]	Cl, 1445 [5b, 5d] (671,680) [a]
R′O, 1442 [5c, 4] (728 [4, a])	PhO, 1378 (715, 700) [7, a]	Ph, 1472 [22]
† R′NH, 1490 [4, 5c, a] (710 [4, a])	R, 1375 (below 650) [6, a]	$ClCH_2$, 1485 [f]
Bu^t·NH, 1493 (<650) [a]	Ar, 1351 (~700) [5c, a]	RNH and R_2N, 1493 [b]
R'_2N, 1493 [b]	R_2N, 1342 (702) [a]	
PhO, 1412 [5c]	RNH, 1351 (702) [a]	X in $(X\cdot B\cdot NPh)_3$
R′, 1410 [5d, c]	R_2SiO, 1380 (735, 720) [a]	Cl, 1375 [5b, 5d]
R'_3Si, 1441 [d]		Ph, 1368 [5d]
$Ar_3'Si$, 1429 [d]		R, 1380 [5b, 5d]
		PhNH, 1497 [a]

X in $(HB\cdot NX)_3$
Ph, 1401 [22]
Me, 1425 (<650) [3]

* R and R′ = alkyl (but not Bu^t for †).

[a] Present work. [b] Niedenzu and Dawson, *J. Amer. Chem. Soc.*, 1959, **81**, 3561. [c] Ryschkewitsch, Harris, and Sisler, *ibid.*, 1958, **80**, 4515. [d] Cowley, Sisler, and Ryschkewitsch, *ibid.*, 1960, **81**, 501. [e] Abel and Singh, *J.*, 1959, 690. [f] Turner, *Chem. and Ind.*, 1958, 1405.

Superior numerals relate to literature references.

EXPERIMENTAL

Preparations.—The borazoles, except for $(Cl\cdot B\cdot NMe)_3$,[22] were prepared by methods described in Parts III and IV.[1,4] The alkylboronic anhydrides,[23] except for the methyl homologue, phenylboronic anhydride,[24] metaborates (Part I [7]), except for $(Bu^tO\cdot BO)_3$, and aminoboroxoles (Part IV [1]) were obtained by published methods.

Methylboronic anhydride. Methylmagnesium iodide (1 mol.) in ether was added to tri-n-butyl borate (1 mol.) in ether at −78°. The bulk of the ether was removed at 20°/20 mm. and the residue was extracted with pentane. The pentane extract afforded dibutyl methylborinate, $(Bu^nO)_2B\cdot Me$, b. p. 80°/20 mm., which was treated with octan-1-ol to afford *dioctyl methylboronate*, b. p. 108°/0·01 mm., n_D^{20} 1·4310 (Found: B, 3·8. $C_{17}H_{37}O_3B$ requires B, 3·8%). To the octyl ester (2 mol.) was added boron trichloride (1 mol.) [$2(RO)_2B\cdot Me + BCl_3 \longrightarrow 2RO(Cl)B\cdot Me + (RO)_2B\cdot Cl$], and the products were decomposed [25] by addition of ferric chloride [$RO(Cl)B\cdot Me \longrightarrow \frac{1}{3}(MeBO)_3 + RCl$; $(RO)_2B\cdot Cl \longrightarrow RCl + \frac{1}{3}(RO\cdot BO)_3$]; the volatile methylboronic anhydride was condensed into a trap in the vacuum-line.

Infrared Spectra.—These were obtained on a Grubb-Parsons S.3A double-beam spectrometer, fitted with a sodium chloride prism. Samples were studied as liquid films, solutions, or mulls in paraffin oil.

The spectra are being submitted to the D.M.S. collection. Data are in the Tables.

We thank Dr. K. G. O'Brien for a sample of t-butyl metaborate, and Dr. R. H. Biddulph and Dr. D. B. Clapp, of Borax Consolidated Ltd., for spectra of ethyl- and isobutyl-boronic anhydride.

FACULTY OF TECHNOLOGY, UNIVERSITY OF MANCHESTER (M. F. L. and H. P.).
NORTHERN POLYTECHNIC, LONDON, N.7 (D. W. A.). [*Received, October 10th*, 1960.]

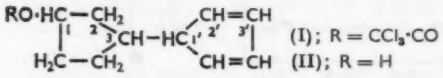
[22] Aubrey and Lappert, unpublished work.
[23] McCusker, Ashby, and Makowski, *J. Amer. Chem. Soc.*, 1957, **79**, 5179.
[24] Bean and Johnson, *J. Amer. Chem. Soc.*, 1932, **54**, 4415.
[25] Lappert, *J.*, 1956, 1768; Brindley, Gerrard, and Lappert, *ibid.*, p. 1540.

374. *Conversion of Cyclopentadiene into New Bicyclopentyl Derivatives; Structure Determination with the Help of Proton Magnetic Resonance Spectroscopy.*

By C. F. Blakely, R. J. Gillespie, L. Roubinek, A. Wassermann, and R. F. M. White.

Cyclopentadiene and trichloroacetic acid react, under specified conditions of concentration, to produce the trichloroacetate (I) of a new alcohol (II) containing two conjugated double bonds. Both the ester and the alcohol are unusually reactive and can be converted into novel polymers. Catalytic hydrogenation of the alcohol (II) gives 3-cyclopentylcyclopentanol which has been converted into 3-cyclopentylcyclopentanone, cyclopentylcyclopentenes, and bicyclopentyl. Proton magnetic resonance spectroscopy in conjunction with the above observations shows that alcohol (II) is 3-(cyclopenta-2,4-dienyl)cyclopentanol.

Diels–Alder diene associations, including the dimerisation of cyclopentadiene, are susceptible to catalysis by trichloroacetic acid [1] with carbonium ions as intermediates.[2] It is now shown that, at sufficiently high trichloroacetic acid concentrations, cyclopentadiene is converted into the trichloroacetate (I) of a new, unusually reactive bicyclopentyl



(I); R = CCl_3·CO (II); R = H

alcohol (II). At low acid concentration [2] the formation of *endo*-dicyclopentadiene predominates. The main purpose of this investigation was to establish the structure of the new ester and of the corresponding alcohol with the help of proton magnetic resonance spectroscopy. In the following paper the mechanism of the reaction leading from cyclopentadiene to the bicyclopentyl derivatives will be discussed. It appears that the same carbonium ion, $C_5H_7^+$, plays a rôle as in the formation of the acid-catalysed Diels–Alder dimerisation.

Experimental

Cyclopentadiene concentrations were estimated by vapour pressure [3] or colorimetric [4] techniques. Trichloroacetic acid titrations were done in benzene, ethanol, or carbon tetrachloride–ethanol, with Bromophenol or Bromothymol Blue as indicator. The bicyclopentyl ester or the alcohol derived from it was used shortly after the final purification. The ester, usually prepared in 30 g. batches, was stored in absence of moisture over solid potassium hydrogen carbonate at −80°: exposure to air was as short as possible. The purification of cyclopentadiene, trichloroacetic acid, and the solvents has been described.[3] Cyclopentanol and ethyl trichloroacetate were commercial samples, dried and redistilled. The dehydration described on p. 1943 was done with activated alumina (type A, mesh $\frac{8}{16}$, of Peter Spence and Sons Ltd.). The catalyst was placed in a vertical tube, the top of which was connected with a separatory funnel from which the alcohol could be slowly released. The products passed through a water condenser, fitted to the lower end of the catalyst tubing, and were collected in traps at −80°. The molecular weight of the ester was estimated by measurements of light scattering and refractive-index increment on a Brice–Phoenix instrument,[4] with a vacuum-filter and light-scattering cell, and a Rayleigh interferometer, adapted for measurements with monochromatic light and for solutions free from molecular oxygen (partial pressure $< 10^{-3}$ mm.). The electronic and infrared spectra were measured with Unicam, Perkin–Elmer, or Grubb–Parsons instruments. Proton nuclear magnetic resonance spectra were obtained with a Varian Associates V-4300 high-resolution instrument, with a 40 Mc./sec. oscillator: a capillary tube containing water

[1] Wassermann, *J.*, 1942, 618.
[2] Rubin, Steiner, and Wassermann, *J.*, 1949, 3046.
[3] Wassermann, *J.*, 1936, 1033.
[4] For calibration and other details see French, Roubinek, and Wassermann, *J.*, 1961, 1953.

XUM

was introduced into the sample tubes to provide an external reference. The spectra were calibrated by the side-band technique. The chemical shifts are given in terms of the dimensionless function δ, defined as $\delta = 10^6[(H_s - H_r)/H_r]$, where H_s and H_r are the resonance field for sample and reference respectively. Values of δ are given as parts per million. Broad lines are due partly to spin–spin interaction and partly to the high viscosity of some of the samples. Peak areas were measured with the help of a planimeter. By using substances of known structure, namely, cyclopentadiene, *endo*- and *exo*-dicyclopentadiene, *exo*-dicyclopentadienol, and cyclopentadienylidenecyclopentane, it was established that the peak-area measurements were accurate within 10—15%.

Results

Stoicheiometry of Reactions between Cyclopentadiene and Trichloroacetic Acid.—Fig. 1 shows that the molar ratio, cyclopentadiene consumed: trichloroacetic acid consumed (α/β), is larger than two if the trichloroacetic acid concentration is below 0·3 mole l.$^{-1}$, while at higher acid

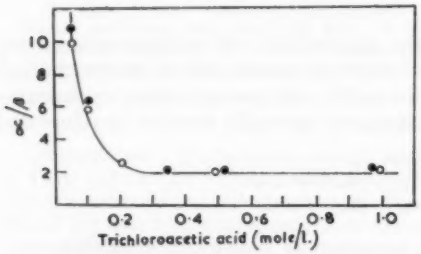


FIG. 1. *Stoicheiometry of reaction between cyclopentadiene and trichloroacetic acid: moles of cyclopentadiene consumed per mole of trichloroacetic acid consumed* (α/β), *plotted against trichloroacetic acid concentration.*

Temp. 20—25°; *Initial concn. of cyclopentadiene,* 1·00—1·31 *mole/l.; cyclopentadiene consumed,* 20·0—40·8%.

● CCl_4 *solution.* ○ C_6H_6 *solution.*

concentrations $\alpha/\beta = 2$, within 5—10%. When α/β exceeded 2, product analyses showed that *endo*-dicyclopentadiene was predominantly formed. A typical experiment of this kind was as follows: A carbon tetrachloride solution (550 c.c.), 0·96M with regard to cyclopentadiene and 0·089M with regard to trichloroacetic acid, was left for 24 days at 20°; M-alcoholic potassium hydroxide (60 c.c.) was then added and the solution concentrated *in vacuo* to 400 c.c., any cyclopentadiene which had not reacted being thereby removed. After 24 hr. at 20° the solution was extracted with water, dried (Na_2SO_4), and fractionally redistilled, *endo*-dicyclopentadiene, b. p. 42°/2·0 mm., being isolated in over 80% yield. The identity of the product was established by its m. p. and mixed m. p. If, on the other hand, α/β is 2·0 ± 0·1, a new reaction, namely, 2 cyclopentadiene + trichloroacetic acid ⟶ ester (I) occurs.

Ester (I).—A dry benzene solution, 0·50M with respect to trichloroacetic acid and 1·0M with respect to cyclopentadiene, was kept for 30 min. at 25° (a temperature rise being prevented by cooling); 40% of the cyclopentadiene was used up. Solid potassium hydrogen carbonate (2 moles per mole of acid) was added. Potassium trichloroacetate was filtered off. The filtrate,[5] was dried (Na_2SO_4) and freed from solvent *in vacuo* below 30°, finally at 1 mm. The residue was 3-(*cyclopenta*-2,4-*dienyl*)*cyclopentyl trichloroacetate* (>90%) (I), n_D^{25} 1·5085 ± 0·005 (mean of 8 determinations), d^{20} 1·29 [Found: C, 48·0; H, 4·4; Cl, 36·3%; equiv. (8 detns.), 290 ± 3. $C_{12}H_{13}Cl_3O_2$ requires C, 48·7; H, 4·4; Cl, 36·0%; equiv., 295·5]. Molecular-weight determinations in carbon tetrachloride at 20° indicated formation of double molecules. This was established by measurements of light scattering and refractive-index increment in absence of molecular oxygen, in carbon tetrachloride solution at 20°, with light of 546 mμ. The ratio R_{90}(solute)/c was (7·7 ± 1·5) × 10^{-5} cm.^{2} g.$^{-1}$ (R being the Rayleigh ratio), if the concentration (c) of ester was between 0·0678 and 0·0989 g. cm.$^{-3}$. The refractive-index increment, extrapolated to $c \longrightarrow 0$, was 0·110 ± 0·005 cm.^{3} g.$^{-1}$. The ester is easily soluble in light petroleum (b. p. 40—60°), ether, acetone, ethanol, chloroform, carbon tetrachloride, cyclohexane, benzene, pyridine, nitrobenzene, or acetic acid, but almost insoluble in water. $\lambda_{max.}$ was 242 mμ in ethanol and 244 mμ in cyclohexane, ε being respectively 802 and 773 l. mole^{-1} cm.$^{-1}$. The ester could not be purified by vacuum-distillation, owing to rapid polymerisation. It solidified

[5] Brown-red owing to a consecutive reaction discussed by Murphy, Roubinek, and Wassermann, *J.*, 1961, 1964.

at about −180° to a glass; by fractional thawing, in the absence of moisture, four fractions were obtained, the equivalent weights, refractive indices, and electronic and nuclear magnetic resonance spectra of which were not significantly different.

Addition of bromine in carbon tetrachloride at 20° to (I) indicates two olefinic double bonds; the time of reaction was 20—120 min. and the initial concentration was 5·8—12·8 × 10^{-3}M with respect to ester and 0·056—0·11N with respect to bromine. Some of the tests were done in absence of molecular oxygen. Hydrobromic acid was estimated (here and below) by the iodate method. In a typical experiment, when 1·28 × 10^{-4} mole of ester and 11·24 c.c. of 0·1N-bromine reacted for 65 min., 6·24 c.c. of bromine solution were used corresponding to the consumption of 4·9 g.-atoms of bromine per mole of ester.

The Alcohol (II).—This was prepared by leaving ester (I) (60 g.) with benzene (20 ml.) and N-alcoholic potassium hydroxide (250 ml.) for 10 min. at 25°, 90% hydrolysis occurring. The mixture was added to aqueous sodium sulphate and extracted with ether; the extract, dried (Na_2SO_4) and evaporated, gave 3-(*cyclopenta*-2,4-*dienyl*)*cyclopentanol* (II), n_D^{25} 1·5105 ± 0·0010, d^{20} 1·025, b. p. 84—86°/0·2 mm., 94—95°/2·0 mm., in ~50% yield if distillation was done quickly, the loss being due to polymerisation [Found: C, 79·9; H, 9·5%; *M* (Rast), 150. $C_{10}H_{14}O$ requires C, 80·0; H, 9·4%; *M*, 150]. The solubility of alcohol (II) is similar to that of ester (I), and $\lambda_{max.}$ in ethanol is 243 mμ (ε 400). A sample of the alcohol purified by steam-distillation had very similar physical constants to those given above. In carbon tetrachloride solution at 20°, it reacted in 2—60 min. with 4·0 ± 0·1 equiv. of bromine (mean of six experiments). The alcohol was converted in the usual way into a 3,5-*dinitrobenzoate*, m. p. 112—113° (from ethanol) (Found: C, 59·0; H, 4·8; N, 8·3. $C_{17}H_{16}N_2O_6$ requires C, 59·3; H, 4·7; N, 8·1%), and a *phenylurethane*, m. p. 64—65° [from light petroleum (b. p. 40—60°) and aqueous ethanol] (Found: C, 75·7; H, 7·2; N, 5·1. $C_{17}H_{19}NO_2$ requires C, 75·8; H, 7·1; N, 5·2%).

Formation of Novel Polymers.—The ester (I), if left at 20° in containers of glass, silica, porcelain, or various metals, with or without atmospheric oxygen or moisture, was gradually converted into bluish-black polymers. Similar reactions took place if the ester was mixed with one of the following substances: tri- or mono-chloroacetic acid, benzoyl peroxide, diphenyl phosphate, copper sulphide, copper or iron powder, various cation-exchangers (H^+ form), charcoal, stannous oxide, Raney nickel, or platinum oxide. The experiments with the last two added materials were done *in vacuo*, in air, and in hydrogen, with shaking. Analyses showed that in most cases the conversion into polymers is accompanied by a liberation of trichloroacetic acid. In no solvent is present, the gradual evaporation of the expelled acid is facilitated by low pressure. Some of the substances added to the ester increase the rate of polymer formation, the most efficient homogeneous catalyst being trichloroacetic acid.[6] The alcohol polymerises with liberation of water. The properties of the polymers prepared from the ester and the alcohol are similar,[7] but the alcohol is less reactive. Polymerisation of the alcohol catalysed by platinum oxide is so slow that during hydrogenation (see below) significant polymerisation did not occur.

Attempts to prepare Maleic Anhydride Adducts.—Dry benzene solutions, 0·3M with respect to ester or alcohol and 0·9M with respect to pure maleic anhydride, were refluxed for 9 hr., with exclusion of atmospheric moisture. In these reactions trichloroacetic acid is liberated from the ester and water from the alcohol. The acid was removed with solid potassium hydrogen carbonate; the water reacted with maleic anhydride and maleic acid crystallised. The solutions, freed from these acids, were evaporated *in vacuo*. The residues were viscous oils, probably polymers, giving neither crystals nor liquids of constant b. p. Similar observations were made when a benzene solution of the ester and maleic anhydride was left for 24 hr. at 20°.

Hydrogenation and Conversion of the Alcohol into a Ketone.—The alcohol (12·3 g.), platinum oxide (0·400 g.), and acetic acid (36 ml.) were shaken with hydrogen at 22°/753 mm. (absorption 3·81 g. per mole; half-time, 13 min.). After removal of the catalyst, and of 80% of the solvent *in vacuo*, the residue was added to an excess of 2N-potassium hydroxide and the product was extracted with ether, recovered, and treated with alcoholic potassium hydroxide to hydrolyse any ester formed. The solution was added to water, which was re-extracted with ether. The extract contained the hydrogenated alcohol and a ketonic impurity ($\nu_{max.}$ 1739 $cm.^{-1}$)

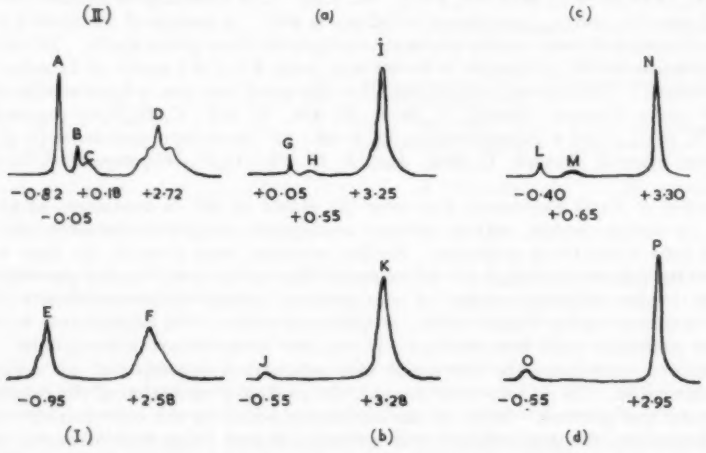
[6] Murphy, Roubinek, and Wassermann, *J.*, 1961, 1964.
[7] French, Roubinek, and Wassermann, *J.*, 1961, 1953.

forming a sparingly soluble 2,4-dinitrophenylhydrazone. The impurity, probably 3-cyclopentylcyclopentanone (see below) formed by reaction of the saturated and the unsaturated alcohol with the platinum oxide, was removed by reduction with sodium at 60—80° in absolute ethanol, added after removal of the ether. The resulting ethanol solution was added to water, and 3-*cyclopentylcyclopentanol* was taken up in ether, washed, dried, and recovered as liquid, b. p. 92°/0·5 mm., 98—99°/1·2 mm., n_D^{25} 1·4844 [Found: C, 78·1; H, 11·6%; *M* (Rast), 151. $C_{10}H_{18}O$ requires C, 77·9; H, 11·8%; *M*, 154].

The saturated alcohol was added, with stirring, to an aqueous solution (600 ml.) at 40°, 0·6M with respect to potassium dichromate and 0·5M with respect to sulphuric acid. After cooling to 20°, the product was taken up in ether, washed, and dried. Recovery gave 3-*cyclopentylcyclopentanone*, b. p. 74—75°/1·3 mm., n_D^{25} 1·4743 (Found: C, 79·1; H, 10·7. $C_{10}H_{16}O$ requires C, 78·9; H, 10·6%).

2-Cyclopentylcyclopentanone and 2-cyclopentylcyclopentanol, prepared as described by Wallach,[8] had b. p. 77°/1·5 mm., n_D^{25} 1·4757, and b. p. 91—92°/2 mm., n_D^{25} 1·4851, respectively.

FIG. 2. *Proton nuclear magnetic resonance spectra for pure liquids at about* 20° (*shifts in p.p.m.*).



(I) *Ester prepared from trichloroacetic acid and cyclopentadiene.* (II) *Alcohol derived from* (I). (a) *Alcohol obtained by hydrogenation of* (II). (b) *Trichloroacetate of the hydrogenated alcohol.* (c) *Cyclopentanol.* (d) *Cyclopentyltrichloroacetate.*

The following derivatives were prepared by standard methods, *e.g.*, phthalates as indicated by Hückel and his collaborators.[9] Phthalates were recrystallised from pentane or light petroleum (b. p. 40—60°), other derivatives from ethanol or aqueous ethanol.

3- and 2-Cyclopentylcyclopentanol gave, respectively, a 3,5-*dinitrobenzoate*, m. p. 79—82° (Found: C, 58·7; H, 5·9; N, 8·4. $C_{17}H_{20}N_2O_6$ requires C, 58·6; H, 5·8; N, 8·05%) and m. p. 69—76° (mixed m. p. 64—68°) (Found: C, 58·1; H, 5·99; N, 8·3%), *phenylurethane*, m. p. 88—92° (Found: C, 74·7; H, 8·5; N, 4·8. $C_{17}H_{23}NO_2$ requires C, 74·6; H, 8·5; N, 5·1%) and m. p. 88—91° (mixed m. p. 82—86°) (Found: C, 74·5; H, 8·3; N, 5·4%), and *hydrogen phthalate*, m. p. 80—82° (from pentane) (Found: C, 71·6; H, 7·4. $C_{18}H_{22}O_4$ requires C, 71·5; H, 7·4%) and m. p. 85—86° (mixed m. p. 74—76°) (from light petroleum) (Found: C, 71·4; H, 7·3%).

3- and 2-Cyclopentylcyclopentanone gave, respectively, a 2,4-*dinitrophenylhydrazone*, m. p. 129—131°, $\lambda_{max.}$ (in EtOH) 232, 362 mμ (ε 20,000) (Found: C, 57·6; H, 5·8; N, 17·2. $C_{16}H_{20}N_4O_4$ requires C, 57·8; H, 6·1; N, 16·9%), and m. p. 158—160° (lit.,[10] 158—159°), $\lambda_{max.}$ and ε as above (Found: C, 57·7; H, 5·95; N, 16·9%), and a *semicarbazone*, m. p. 197—

[8] Wallach, *Annalen*, 1912, **389**, 178.
[9] Hueckel, Neunhoffer, Gercke, and Frank, *Annalen*, 1929, **477**, 135.
[10] Knight, Donald, and Cram, *J. Amer. Chem. Soc.*, 1954, **76**, 1643.

198° (Found: C, 63·4; H, 9·5; N, 20·3. $C_{11}H_{19}N_3O$ requires C, 63·1; H, 9·15; N, 20·1%) and m. p. 209° (mixed m. p. 184—186°) (lit.,[11] m. p. 208—209°).

The crude 3-cyclopentylcyclopentanol was oxidised to a crude ketone, whose dinitrophenylhydrazone and semicarbazone on systematic crystallisations gave only the derivatives of 3-cyclopentylcyclopentanone. It is concluded that the unsaturated alcohol is not contaminated with an isomer which, after hydrogenation, can be oxidised to 2-cyclopentylcyclopentanone. The interest of this is discussed in the following paper.

3-Cyclopentylcyclopentanol with trichloroacetyl chloride in pyridine and carbon tetrachloride at 20° (3·5 hr.) gave, on the usual working-up, its *trichloroacetate* as a colourless liquid (Found: C, 48·7; H, 5·4; Cl, 36·1. $C_{12}H_{17}Cl_3O_2$ requires C, 48·1; H, 5·7; Cl, 35·5%).

Dehydration of 3-Cyclopentylcyclopentanol and Conversion into Bicyclopentyl.—The alcohol (7 g.) was passed at 340°/41 mm. over activated alumina (100 g.), the reaction time being 17 min. The products were water and a mixture of cyclopentylcyclopentenes, b. p. 112—115°/100 mm., n_D^{25} 1·4796 (Found: C, 88·1; H, 12·0. Calc. for $C_{10}H_{16}$: C, 88·2; H, 11·8%). A similar mixture, prepared as described by von Braun *et al.*,[12] had b. p. 186°/763 mm., n_D^{25} 1·4738. Our mixture (3·8 g.), platinum oxide (0·14 g.), and ethyl acetate (14 ml.) were shaken with hydrogen for 18 hr. at 22°/767 mm. (absorption 1·8 g. per mole). After removal of the catalyst, and of the solvent *in vacuo*, the residue was dissolved in cyclohexane and treated with sulphuric acid, water, calcium chloride, and sodium at 80°. After filtration from sodium and removal of the solvent *in vacuo*, bicyclopentyl, b. p. 94—95°/46 mm., n_D^{25} 1·4631, was

TABLE 1. *Infrared absorption spectra* ($cm.^{-1}$; s = <50% *transmission*).

Key: I, 3-(Cyclopenta-2,4-dienyl)cyclopentyl trichloroacetate.
II, 3-(Cyclopenta-2,4-dienyl)cyclopentanol.
III, 3-Cyclopentylcyclopentanol.
IV, 3-Cyclopentylcyclopentanone.
V, 2-Cyclopentylcyclopentanone.
VI, 2-Cyclopentylcyclopentanol.
VII, Mixed cyclopentylcyclopentenes [from (III)].
VIII, ,, ,, (von Braun *et al.*).
IX, Bicyclopentyl.

(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
3058	3279s	3333s	3448	3448	3333s	3049	3049	2944s
2941	2985s	2941s	2959s	2959s	2941s	2941s	2950s	2857s
2857	2907s	1443s	2857s	2857s	2857s	2865s	2857s	1471
1754s	2817s	1333s	1739s	1739s	1443s	1634	1613	1447s
1613	1618	1294	1449s	1449s	1333s	1600	1449s	1359
1238s	1445s	1238	1408s	1408s	1235	1437s	1370	1326
1010	1418	1190	1364	1361	1190	1335	1351	1299
1005	1355s	1163	1330	1333	1136	1312	1316	1250
971	1319	1101	1307	1316	1071s	1285	1289	1026
909								
877s	1266	1067s	1274s	1274s	1024s	1200	1220	963
833s	1205	1008s	1250	1242	971s	1157	935	926
826s	1183	990	1235	1208	917	1031	909	893
680s	1152	935	1156s	1193	900	943	893	
730	1109	900	1096	1156s	885	926	719s	
	1077	893	1018	1124	870	900		
	1053	840	1000	1081	781	893		
	1032		971	1020		800		
	1005s		935	1000		719s		
	943		893	935				
	909		885	909				
	734		826	893				
	725s		813	826				
	699s		758					

obtained (Found: C, 87·1; H, 13·1. Calc. for $C_{10}H_{18}$: C, 86·9; H, 13·1%). The cyclopentylcyclopentenes, prepared by the method of von Braun *et al.* gave, on hydrogenation, a product with identical analysis, b. p., *n*, and infrared spectrum.

[11] Hückel, Gross, and Doll, *Rec. Trav. chim.*, 1938, **57**, 557.
[12] von Braun, Kamp, and Kopp, *Ber.*, 1937, **70**, 1756. We have found by vapour-phase chromatography that the "cyclopentylcyclopentene" of these authors is a mixture of isomers; see also Roubinek, Ph.D. Thesis, London, 1960.

XUM

Cyclopentyl Trichloroacetate.—Prepared as above, this had b. p. 60—61°/0·4 mm. (Found: C, 36·8; H, 4·1; Cl, 45·2. $C_7H_9Cl_3O_2$ requires C, 36·3; H, 3·9; Cl, 45·9%).

Infrared Absorption Spectra.—These were determined at about 20° for the pure liquids without solvent. The results are in Table 1.

Proton Magnetic Resonance Spectra.—These are in Fig. 2, peaks being designated A—P. The spectra of cyclopentanol and its 3-substituted derivatives were measured both for the

TABLE 2. *Influence of carbon tetrachloride on proton magnetic resonance of 3-(cyclopenta-2,4-dienyl)cyclopentanol* (II) *at about* 20°.

	Position of peak (p.p.m.)			
	A	C	D	B
Pure liquid state	−0·82	+0·18	+2·72	−0·05
~1 : 1 mixture with CCl_4	−0·90	+0·10	+2·65	+0·52

TABLE 3. *Observed peak area ratios of spectra in the pure liquid state.*

	A/(B + C)	D/(A + B + C)	F/E
Alcohol (II)	2·0	1·5	
Its trichloroacetate			1·8

pure liquid state and for CCl_4 solutions (about 50% by volume). The influence of this solvent on the spectrum of alcohol (II) is shown in Table 2. A similar effect was observed with the saturated bicyclic alcohol and cyclopentanol, the peaks which moved to higher field strength being G and L. Relative peak areas of the spectra of alcohol (II) and its trichloroacetate are recorded in Table 3. It was not possible to determine the areas of peaks B and C separately, because they overlap. For reasons explained below, we have also measured the proton magnetic resonance spectrum of ethyl trichloroacetate and compared it with that of ethanol; the methylene quartet and methyl triplet in the spectra of this ester are shifted respectively 1·20 and 0·60 p.p.m. to lower field relative to the corresponding peaks of ethanol.

DISCUSSION

The similarity, among the chemical classes, of the infrared spectra recorded in Table 1 for the various saturated alcohols, the ketones, and the hydrocarbons makes it probable that all these and therefore also the unsaturated alcohol (II) and its trichloroacetate (I), are bicyclopentyl derivatives. This is proved by the conversion of the saturated 3-cyclopentylcyclopentanol into bicyclopentyl. This alcohol is not identical with 2-cyclopentylcyclopentanol, nor is the ketone derived from the former identical with that derived from the latter, either in infrared spectra, refractive indices, and b. p., or in the m. p.s of the crystalline derivatives. The structures of the saturated alcohol (III) and ketone (IV) are thus proved.

The hydrogenation and bromination of the unsaturated alcohol (II) and its ester (I) prove that two double bonds per mole are present. These must be conjugated because the electronic spectra of both have peaks at 243—244 mμ.* Two conjugated double bonds can be incorporated into these bicyclopentyl derivatives in ten different ways. To decide between these possibilities, assignment of the peaks of the proton magnetic resonance spectra was considered. The alcohol (II) shows peaks A and D at −0·82 and +2·72 p.p.m., which are assigned [13] to hydrogen atoms bound respectively to unsaturated and saturated carbon. The corresponding hydrogenated alcohol showed no peak in the region −0·82 p.p.m. Addition of carbon tetrachloride to the pure liquid unsaturated alcohol (II) shifted peak B to higher field (see Table 2), while the other peaks move in the opposite direction. The former shift is characteristic of hydrogen-bonded alcoholic hydroxyl,[14]

* The relatively large $\varepsilon_{max.}$ value of ester, compared to that of alcohol, may be due to different stereochemical configurations.

[13] Meyer, Saika, and Gatowsky, *J. Amer. Chem. Soc.*, 1953, **76**, 4567.

[14] Cohen and Reid, *J. Chem. Phys.*, 1956, **25**, 790; Becker, Liddel, and Stoner, *J. Mol. Spectroscopy*, 1958, **2**, 1.

XUM

and therefore peak B is taken to be the signal of hydroxyl-hydrogen. To account for the ratio of line areas A/(B + C) (see Table 3), peak C must be due to a single hydrogen atom. The effect brought about by conversion of the alcohol (II) into its trichloroacetate shows that peak C must be assigned to a hydrogen atom bound, together with hydroxyl, to a saturated carbon atom.

This interpretation is confirmed by the spectra of the saturated bicyclic alcohol (III) and cyclopentanol itself: peaks G and L are assigned to hydroxyl-hydrogen, because of the effect produced by carbon tetrachloride, while peaks H and M are taken to correspond to C, peaks I and N being the signals of the other hydrogen atoms.

There are only two peaks, E and F, in the spectrum of the unsaturated ester, at −0·95 and +2·58 p.p.m., the signals corresponding to peaks B and C being absent. The disappearance, on esterification, of a peak due to hydroxyl-hydrogen is to be expected, but that of the other peak has to be explained with reference to the spectra of 3-cyclopentylcyclopentanol, cyclopentanol, and ethanol, and their trichloroacetates. For the spectra of these two cyclic alcohols and their esters peaks H, J, M, and O are assigned to hydrogen bound with either hydroxyl or trichloroacetoxyl to saturated carbon. Substitution of the electron-withdrawing trichloroacetoxyl group for hydroxyl produces a shift of the relevant peaks to lower field: this is 1·10 p.p.m. for the bicyclic alcohol (III) and its ester, 1·20 p.p.m. for the monocyclic alcohol and its ester (XI), the shifts on passing from ethanol to its ester having been specified on p. 1944. In view of all these observations it is assumed that in passing from the unsaturated alcohol (II) to its ester (I) the peak corresponding to C is shifted to about −1·00 p.p.m., so that it coincides in this ester with the peak due to hydrogen bound to unsaturated carbon. Peak E is assigned, therefore, to hydrogen at unsaturated carbon and to hydrogen bound together with trichloroacetate to saturated carbon, while peak F is due to the other hydrogen atoms.

These assignments exclude those four of the ten possibilities that have a double bond attached at positions 1 and 1′. Moreover, such formulæ should require keto–enol equilibrium for the alcohol and therefore a carbonyl frequency in its infrared spectrum, and this is not observed. To decide between the remaining six formulæ, their calculated peak-area ratios (Table 4) are compared with the observed values shown in Table 3. The last

TABLE 4. *Calculated peak-area ratios of proton nuclear magnetic resonance spectra for six of the ten possible doubly unsaturated derivatives of 3-hydroxybicyclopentyl.*

Posn. of double bonds	Calc. peak-area ratios A/(B + C)	D/(A + B + C)	F/E	Posn. of double bonds	Calc. peak-area ratio A/(B + C)	D/(A + B + C)	F/E
3′—4′; 1′—5′	1·5	1·8	2·25	3—4 1′—2′	1·0	2·5	3·33
4′—5′; 3—1′	1·0	2·5	3·33	2—3; 1′—5′	1·0	2·5	3·33
4—5; 3—1′	1·0	2·5	3·33	2′—3′; 4′—5′	2·0	1·33	1·6

structure in Table 4 is the only one for which the two sets of values agree within the limits of the experimental error. Further, the observed ratio of peak areas A/(B + C) is 2·0; since peak B is due to one hydrogen atom and there are only two double bonds in the molecule, peak A must be due to four hydrogen atoms and peak C to one hydrogen atom. The last structure in Table 4 is the only one having four hydrogen atoms attached to unsaturated carbon atoms. It is concluded, therefore, that the correct formula of the cyclopentadienylcyclopentanol is as shown in formula (II).

Thanks are offered to the Wellcome Trust for the loan of the nuclear magnetic resonance spectrometer, to the Zinc Corporation for a Fellowship (to R. F. M. W.), and to the Czech Refugee Trust Fund for an award (to L. R.).

WILLIAM RAMSAY AND RALPH FORSTER LABORATORIES,
UNIVERSITY COLLEGE,
GOWER ST., LONDON, W.C.1.

[*Received, May 18th,* 1960.]

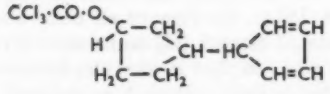
XUM

375. *Kinetics and Mechanism of the Formation of a Novel Bicyclopentyl Derivative: Rôle of Carbonium Ions in the Reaction between Cyclopentadiene and Trichloracetic Acid.*

By C. F. Blakely and Albert Wassermann.

A vapour-pressure technique has been developed to study the kinetics of the conversion of cyclopentadiene and trichloroacetic acid into 3-(cyclopenta-2,4-dienyl)-cyclopentyl trichloroacetate, in non-polar and polar solvents, at different temperatures, without and with oxygen, and in the presence of added substances. The observations are explained by a mechanism involving proton-transfer with formation of carbonium-ion intermediates. This accounts for the structure of the novel bicyclopentyl derivative and for the fact that it is formed only if the trichloroacetic acid concentration is high.

In the preceding paper [1] the conversion of trichloroacetic acid and cyclopentadiene into 3-(cyclopenta-2,4-dienyl)cyclopentyl trichloroacetate (I) is described. In this product which is formed only if the trichloroacetic acid concentration is relatively high, the two five-membered rings are united by a single carbon–carbon bond. In the Diels–Alder dimeris-



(I)

ation of cyclopentadiene, on the other hand, which occurs either without acid [2] or at low acid concentration,[3] the two reactants are linked together by two bonds. It is the purpose of this investigation to establish the mechanism of the formation of ester (I) and to explain why the stoicheiometry depends on the acid concentration.

Experimental

Trichloroacetic acid in carbon tetrachloride was introduced into a round-bottomed flask, fitted with a tap and ground joint, by which it could be connected with a vacuum-line; the solvent was slowly distilled off, thereby affording the acid as a film, which was dried at $\sim 30°/10^{-3}$ mm. Redistilled dry solvent and cyclopentadiene [the latter dried over Na_2SO_4—$Mg(ClO_4)_2$] were freed from air by cooling, evacuation to 10^{-2} mm., and thawing *in vacuo*, these operations being repeated four times. The acid film in the evacuated vessel was cooled and air-free solvent and cyclopentadiene were added by bulb-to-bulb distillation *in vacuo*, in such a manner that the cooled reaction vessel contained solid layers of acid and cyclopentadiene, separated by solid solvent. Taps and ground joints were coated with sugar grease.[4] The reaction vessel was attached to a mercury manometer, as shown in Fig. 1, and reaction was started by thawing and rapid mixing. The concentrations were calculated from the known weights of the components. The size and shape of the vessels was such that they could be fitted on an analytical balance. For conversion into molarites, specific gravities of appropriate solutions were measured (solutions used for these experiments were not freed from air). The temperature of the water-thermostat, into which manometer and reaction vessel were introduced, was constant within $\pm 0{\cdot}01°$. The brass plate shown in Fig. 1 was fitted into the thermostat in a manner safeguarding its vertical position and permitting shaking, so that equilibrium between liquid and gas phase was established. Readings of illuminated mercury levels were made through a glass window of the thermostat with the help of a lens fitted with cross-wires. The mercury was frequently tapped to prevent sticking. The reproducibility of readings was $\pm 0{\cdot}1$ mm. The sugar grease was protected from water by coating of the outside of taps and ground joints with Vaseline.

[1] Blakely, Gillespie, Roubinek, Wassermann, and White, preceding paper.
[2] Kauffmann and Wassermann, *J.*, 1939, 870.
[3] Wassermann, *J.*, 1942, 618; Rubin, Steiner, and Wassermann, *J.*, 1949, 3046.
[4] Meloche and Frederick, *J. Amer. Chem. Soc.*, 1932, **54**, 3264.

XUM

If P_0, P_t, and P_∞ are the vapour pressures of the reaction mixture, at zero time, time t, and at the end of the reaction, then x, the concentration of cyclopentadiene consumed at time t, is given by

$$x = b[(P_0 - P_t)/(P_0 - P_\infty)] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where b is the initial concentration of cyclopentadiene. In most runs P_0 was determined by back-extrapolation of P_t to zero time, the time interval between thawing of the reaction mixture and zero time being measured with cyclopentadiene solution free from acid. When the acid concentration and the temperature were not too high, then P_0 could be directly observed and agreed with $P_0' - \Delta P$, where P_0' is the vapour pressure of an acid-free cyclopentadiene solution of the appropriate concentration and ΔP is the experimentally determined difference between the vapour pressure of the solvent and that of the trichloroacetic acid solution. If the rate of reaction was sufficiently high, then P_∞ was taken to be the steady-state vapour pressure at the end of reaction. In most experiments, however, the approach to the steady state was

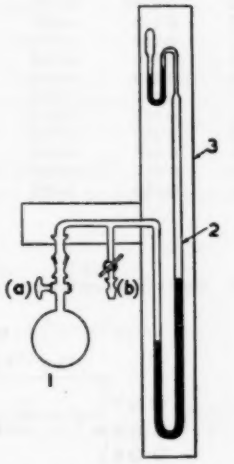


FIG. 1. *Apparatus*: (1) *Reaction vessel; capacity about* 100 *ml., containing* 20—40 *ml. of solution.* (2) *Mercury manometer.* (3) *Polished brass plate on which manometer was fixed; two* 80 cm. *scales (not shown), divided in* 0·1 *cm., were etched on the plate, at positions adjoining the two manometer arms. Tap* (a) *remained closed, while the manometer was evacuated through* (b). *At this stage the reaction mixture in vessel* (1) *was still frozen. After tap* (b) *had been closed and tap* (a) *opened, the whole apparatus was immersed in the thermostat (see text).*

so slow that P_∞ was calculated from the vapour pressure of trichloroacetic acid solutions containing the product of the reaction. It was established that the partial vapour pressure of cyclopentadiene is a linear function of its concentration. The validity of expression (I) was confirmed, furthermore, by calculating x from the results of colorimetric measurements.[5] The results of experiments carried out by the two techniques agreed to within $\pm 2\%$. In experiments with molecular oxygen the reaction mixture was prepared *in vacuo*, as described. Vessel (1) (Fig. 1) containing the frozen components was connected with them anometer, tap (a) being closed. Tap (b) was opened, and the manometer was evacuated and filled with oxygen from a reservoir. Tap (b) was closed, (a) was opened, and, after equilibration with the thawed solution, the oxygen concentration in solution could be calculated from manometer readings, temperature, and the dimension of the apparatus. In these experiments x was calculated from the results of colorimetric measurements.[5]

RESULTS

In each solvent and at each temperature, preliminary experiments, such as those described before,[1] were carried out to establish that, under the specified concentration conditions, 3-(cyclopenta-2,4-dienyl)cyclopentyl trichloroacetate (I) rather than *endo*-dicyclopentadiene is the main product. The rate of formation of ester (I) is given by:

$$dx_4/dt = k(a - x/2)^2(b - x)$$

[5] Wassermann, *J.*, 1936, 1033.

XUM

which on integration gives:

$$k = \frac{1}{t}\left(\frac{9{\cdot}21}{(b-2a)^2}\right)\log_{10}\left\{\left(\frac{1-x/2a}{1-x/b}\right) - \frac{2}{a(b-2a)}\left[\frac{x/2a}{(1-x/2a)}\right]\right\} \quad . \quad . \quad (2)$$

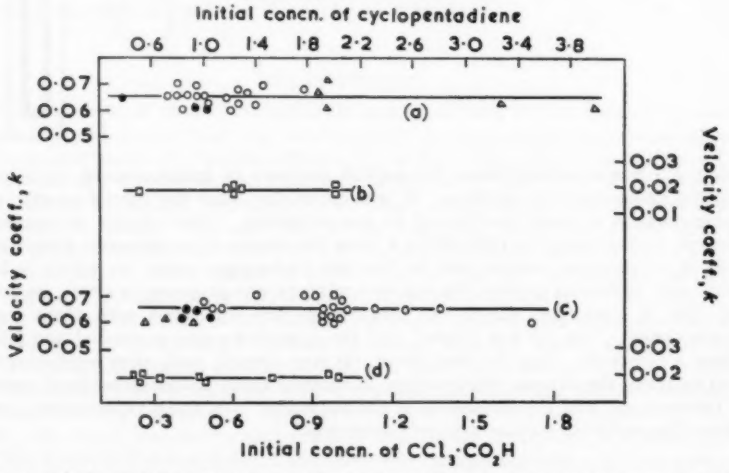
where a and b are the initial concentrations of acid and cyclopentadiene. In most runs the k values increased or decreased with increasing conversion, which is due to the influence of a

TABLE 1. *Rate of reaction between cyclopentadiene and trichloroacetic acid.*

Results of typical experiments. Solvent C_6H_6, 20·0° in (A) and (B); solvent CCl_4, 25·1° in (C). Initial concn. (mole/l.) of cyclopentadiene: 0·717 (A); 0·955 (B); 0·984 (C). Initial concn. (mole/l.) of $CCl_3{\cdot}CO_2H$: 0·988 (A); 0·354 (B); 0·978 (C). % Conversion: 13·6—98·5 (A); 4·3—31·3 (B); 3·8—65·9 (C). Extrapolated and mean k values (l.^{2} mole^{-2} min.$^{-1}$): 0·066 (A); 0·062 (B); 0·020 (C). t (time), X, and k are given in min., mole l.$^{-1}$, and l.^{2} mole^{-2} min.$^{-1}$, respectively.

A			B			C		
t	X	k	t	X	k	t	X	k
2	0·0909	0·073	6	0·0409	0·062	2	0·0376	0·021
3	0·143	0·082	9	0·0595	0·062	5	0·0888	0·021
4	0·182	0·083	17	0·0966	0·058	6	0·109	0·022
5	0·210	0·083	21	0·115	0·059	8	0·120	0·018
6	0·266	0·093	33	0·141	0·049	10	0·161	0·020
7	0·287	0·089	57	0·208	0·049	12	0·181	0·020
10	0·367	0·093	102	0·282	0·047	14	0·198	0·019
14	0·437	0·092	118	0·301	0·046	17	0·243	0·020
18	0·493	0·093				20	0·273	0·020
21	0·511	0·087				25	0·311	0·019
24	0·542	0·093				30	0·359	0·020
						41	0·454	0·021
						57	0·557	0·022
						76	0·649	0·024

FIG. 2. *Rate of reaction between cyclopentadiene and trichloroacetic acid in benzene and carbon tetrachloride. Influence of initial concentration.*



Ordinates: velocity coefficient, k (in l.^{2} mole^{-2} min.$^{-1}$). Upper abscissa: initial concn. (mole l.$^{-1}$) of cyclopentadiene. Lower abscissa: initial concn. of trichloroacetic acid.

Graphs (a) *and* (b) *relate to upper abscissa; graphs* (c) *and* (d) *relate to lower abscissa.*

Symbols △, ●, ○ *relate to left ordinate; benzene solution, 20·0°.*
Symbol □ *relates to right ordinate; carbon tetrachloride, 25·1°.*

In the experiments designated by ● *and* □, *k did not significantly vary in each run; in the experiments designed by* △ *and* ○, *k decreased or increased with time, the value in the Figure being obtained by back-extrapolation to zero conversion.*

For % conversion, and trend of k values, in each run, see Tables 12, 13, *and* 15 *of Blakeley's Ph.D. Thesis (London, 1957).*

consecutive reaction,[6] or of the product which acts as retarder (see Table 3). When there was a trend of the velocity coefficients, back-extrapolation to zero conversion was carried out. For carbon tetrachloride solutions below 35°, the k values showed no significant trend. There was no indication that under the conditions of these experiments decomposition of ester (I) into trichloroacetic acid and cyclopentadiene is significant. The accuracy of the velocity coefficients in the following Tables and Figures is $\pm 5\%$ if there was no trend, $\pm 10\%$ if a back-extrapolation had to be carried out, and about $\pm 15\%$ in a few runs at relatively high temperatures or concentrations where the initial vapour pressures of the solution could not be directly determined but had to be estimated by extrapolation or interpolation. The results of three typical experiments are in Table 1 and the dependence of the extrapolated or mean velocity coefficients on the initial concentrations (test of rate equation 2) is shown in Fig. 2. The influence of temperature was established by experiments at four temperatures between 20° and 45°, the Arrhenius rate equation, $k = A \exp(-E/RT)$, being obeyed. The numerical value of the two parameters (A, in l.^{2} mole^{-2} sec.$^{-1}$, and E in cals. mole^{-1}) are as follows:

$$\left.\begin{array}{ll} C_6H_6: & \log_{10} A = 4{\cdot}3 \pm 0{\cdot}4;\ E = 9900 \pm 500 \\ CCl_4: & \log_{10} A = 4{\cdot}4 \pm 0{\cdot}4;\ E = 9700 \pm 500 \end{array}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Sixteen experiments were carried out, which showed that molecular oxygen does not influence the rate of formation of ester (I), the ratio moles of cyclopentadiene/moles of oxygen in the reaction mixture, at zero time, being varied from 68 to $>10^5$. Table 2 shows that the polar

TABLE 2. *Rate of reaction between cyclopentadiene and trichloroacetic acid in benzene–nitrobenzene and nitromethane.* Initial concns. (mole l.$^{-1}$) of cyclopentadiene and trichloroacetic acid between 0·849 and 1·126; 20·0°.

Solvent	C_6H_6–$PhNO_2$					$MeNO_2$
Concn. of $PhNO_2$	0·00	0·805	1·292	2·295	3·650	—
k (l.^{2} mole^{-2} min.$^{-1}$)	0·07	0·1	0·2	0·3	0·6	0·3

TABLE 3. *Rate of reaction between cyclopentadiene and trichloroacetic acid in the presence of added substances.*

Addendum	Initial concn. (mole l.$^{-1}$) C_5H_6	$CCl_3{\cdot}CO_2H$	Addendum	k (l.^{2} mole^{-2} min.$^{-1}$)	Retardation (%)
		At 20° in C_6H_6.			
H_2O	0·880	0·941	2·74[a]		90
,,	1·03	0·971	0·973		90
,,	0·933	1·00	0·623		70
,,	0·975	0·971	0·282		30
MeOH	0·949	0·954	0·877		90
,,	0·885	0·980	0·541		70
,,	0·926	0·963	0·398		60
,,	0·825	0·964	0·130		20
Dioxan	0·945	0·964	0·995		90
,,	0·905	0·953	0·398		90
$COMe_2$	0·912	0·982	0·904		90
,,	0·963	0·962	0·421		60
$CHCl_3$	0·907	0·998	0·934	0·09[b]	—
Bz_2O_2	0·991	0·917	0·249		30
Cyclopentadiene polymer[c]	0·950	0·999	0·006	0·08	—
8 g. glass powder[d]	1·10	0·980	—	0·09	—
Glass tubes[e]	0·852	0·993	—	0·08	
		At 25° in CCl_4.			
Ester (I)	1·31	0·506	0·845		75

[a] This molarity is computed on the assumption that all the added water is dissolved; in fact, only partial dissolution occurred. [b] In an experiment in chloroform solution at 20° (initial concn. of cyclopentadiene and trichloroacetic acid, respectively, 0·924 and 0·976 mole l.$^{-1}$), k was 0·03 l.^{2} mole^{-2} min.$^{-1}$. [c] Prepared by stannic chloride-catalysis in chloroform solution; average molecular weight 5×10^4. [d] Total volume of reaction mixture 11·0 c.c. [e] The length and diameter of the tubes were adjusted in such a way that the surface–volume ratio was twice as great as in the tests without added glass.

[6] Murphy, Roubinek, and Wassermann, *J.*, 1931, 1964.

aprotic solvents nitrobenzene and nitromethane increase the rate of reaction. The influence of other added substances is shown in Table 3: water, various " basic " solvents, benzoyl peroxide, or the product of the reaction act as retarders, while addition of glass or of a cyclopentadiene polymer made by stannic chloride-catalysis had no significant influence. The percentage retardation in Table 3 was calculated from $100(k - k_r)/k$ where k and k_r are velocity coefficients without and with retarders. For the present purpose both velocity coefficients were calculated from eqn. (2), k_r being the mean of the observed values relating to 20% and 40% conversion.

It could be suggested that the primary product of the reaction between cyclopentadiene and trichloroacetic acid is dicyclopentadiene which is converted into ester (I) in a consecutive reaction if the acid concentration is sufficiently high. This possibility is ruled out by unpublished experiments, which show that the reaction between dicyclopentadiene and trichloroacetic acid produces, not ester (I), but the trichloroacetic acid ester of *exo*-dihydrohydroxydicyclopentadiene, the ratio of the rate of formation of ester (I) and of this ester being about 10^4. The dicyclopentadiene alcohol is known from previous work; [7] it is different from the alcohol obtained from our ester and described in the preceding paper.[1]

Discussion

Stoicheiometry and Mechanism.—The observed rate equations of the trichloroacetic acid-catalysed dimerisation of cyclopentadiene [3] and of the formation of ester (I) are

$$d[\text{Dimer}]/dt = k_d[C_5H_6][CCl_3{\cdot}CO_2H] \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$d[\text{Ester (I)}]/dt = k[C_5H_6][CCl_3{\cdot}CO_2H]^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

If experiments in carbon tetrachloride at 25° are carried out with 0·0050M- and 1·0M-trichloroacetic acid it follows from the specified numerical values of k_d and k that the ratios $d[\text{Dimer}]/dt/d[\text{Ester (I)}]/dt = k_d/k[CCl_3{\cdot}CO_2H]$ are respectively $4{\cdot}4 \pm 0{\cdot}8$ and $0{\cdot}022 \pm 0{\cdot}004$. It is understandable, therefore, why the preparative isolation of ester (I) is only possible if the trichloroacetic acid concentration is sufficiently high.[1]

Rate equations (4) and (5) are consistent with the following reactions:

$$\text{M} + \text{HB} \underset{k_1'}{\overset{k_1}{\rightleftharpoons}} i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{I})$$

$$\text{i} + \text{M} \underset{k_2'}{\overset{k_2}{\rightleftharpoons}} i' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{II})$$

$$\text{i}' \underset{k_3'}{\overset{k_3}{\rightleftharpoons}} \textit{endo}\text{-dicyclopentadiene (dimer)} + \text{HB} \quad . \quad . \quad . \quad (\text{III})$$

$$\text{i}' + \text{HB} \underset{k_4'}{\overset{k_4}{\rightleftharpoons}} i'' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{IV})$$

$$\text{i}'' \underset{k_5'}{\overset{k_5}{\rightleftharpoons}} \text{Ester (I)} + \text{HB} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{V})$$

where M is cyclopentadiene, HB is trichloroacetic acid (the base B being the trichloroacetate ion), i and i′ are singly charged ion pairs, $C_5H_7^+ \cdots B^-$ and $C_{10}H_{13}^+ \cdots B^-$, and i″ is a doubly charged ion pair $C_{10}H_{14}^{2+} \cdots 2B^-$. The structure $C_{10}H_{13}^+ \cdots \overbrace{B\ HB}^{-}$, rather than $C_{10}H_{14}^{2+} \cdots 2B^-$, could perhaps be suggested for i″; the doubly charged ion pair formula is however preferred, because it fulfils the structural requirements to be discussed below, but the kinetic feature of this reaction can be accounted for by both types of intermediate. The cations and anions of these ion pairs must be held firmly together, if the dielectric constant of the solvent is low. Application of the stationary-state approximation leads, as in similar problems, to a complicated rate equation, which can be reconciled with the

[7] Bruson and Riener, *J. Amer. Chem. Soc.*, 1945, **67**, 725; Bartlett and Schneider, *ibid.*, 1946, **68**, 6.

experimental expressions, if arbitrary assumptions are made. These are in the present case * as follows

$$\left.\begin{aligned} k_1[\mathrm{M}][\mathrm{HB}] &\gg k_2'[\mathrm{i}'] \\ k_2[\mathrm{i}][\mathrm{M}] &\gg \{k_4'[\mathrm{i}''] + k_3'[\mathrm{Dimer}]\} \\ k_3 &\gg k_2' \text{ or } k_4[\mathrm{HB}] \\ k_4[\mathrm{i}'] &\gg k_5'[\mathrm{Ester\ (I)}] \\ k_2[\mathrm{M}] &\gg k_1' \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Assumptions (6) are justified because they lead to the experimental rate equations (4) and (5) with $k_d = k_1$ and

$$k = k_1k_4k_5/(k_4' + k_5)k_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Furthermore, k, according to eqn. (7), is compatible with the observed A factors and the influence of solvent polarity, as shown below.

Kinetic A Factors.—If each velocity coefficient of eqn. (7) is expressed by the appropriate product of non-exponential and exponential factors, the over-all A values (3 above) are given by $A_1A_4A_5/(A'_4 + A_5)A_3$, where A_1 and A_4 relate to the bimolecular formation of the ion pairs in eqn. (I) and (IV), while A_3, A_5, and A'_4 relate to (III), (V), and the reverse reaction (IV). If these were " normal " unimolecular processes, A_3, A'_4, and A_5 should be about 10^{13} sec.$^{-1}$, whence it follows from (3) that $A_1 \times A_4 \approx 10^{17}$ l.^{2} mole^{-2} sec.$^{-2}$. A_1 is about 10^{-1} l. mole^{-1} sec.$^{-1}$ (see ref. 3), so that $A_4 \approx 10^{18}$ l. mole^{-1} sec.$^{-1}$, which is much too large, for the following reason: (IV) involves a charge separation, and therefore an increased solvation of the transition state, which is assumed to be similar to i''; this, in turn, should give rise to a negative entropy of activation and to a non-exponential A factor smaller than 10^{11} l. mole^{-1} sec.$^{-1}$. It is concluded that $A_5 \gg A'_4$ and $A_3 \gg 10^{13}$, so that $A_4 \ll 10^{18}$. The first inequality can be related to desolvation of the transition state in (V), owing to the collapse of the ion pair, it being assumed as before that transition and final states are similar. The " release " of solvent molecules will increase the entropy of activation and thus A_5 will be relatively large. The second inequality cannot be explained by solvation effects, but is explained by a low configurational entropy of the transition state in (III), which may over-compensate an opposing influence of " desolvation." If the transition state in (III) is similar to *endo*-dicyclopentadiene, a low configurational entropy is to be expected, because the intermediate i', the structure of which will be discussed below, cannot be so " stiff " as dicyclopentadiene, in which a number of low vibrational modes are prevented by the two bonds which unite the five-membered rings.

Influence of Polarity of Solvent.—According to Bruson *et al.*,[7] the over-all activation energy, E, of the formation of ester (I) is given by $E = (E_2 + E_4 + E_5) - [(E_4' \text{ or } E_5) + E_3]$, where the subscripts have the same significance as above. E_1 and E_4 relate to eqn. (I) and (IV), in which a charge separation occurs, while E_3, E_4', and E_5 are the activation energies of (III), of the reverse reaction (IV) and of (V), in which either electrically neutral species are formed from the ion pairs i' and i'' or a doubly charged ion pair is transformed into a singly charged ion. Reactions (I) and (IV) should be facilitated if the solvent is made more polar, while in the other reactions the situation is reversed. If we assume that in all cases the transition and the final state are similar, it can be expected that E_2 and E_4 will decrease with increasing polarity of the solvent, while the trend of E_3, E_4', and E_5 will be in the opposite direction. The influence of the activation energy is probably more important than opposing effects, owing to the entropy of activation, and it would follow, therefore, that an increase in the polarity of the solvent should increase k_1 and k_4 and decrease k_2, k_4', and k_5. The figures in Table 3 show that the over-all rate constant, k, increases with increasing polarity of the solvent. This is consistent with

* A search for a set of assumptions different from (6) was not successful.

XUM

the suggested mechanism if the trend of $k_1k_4/(k_4' + k_5)k_3$ rather than that of k_5 is decisive.

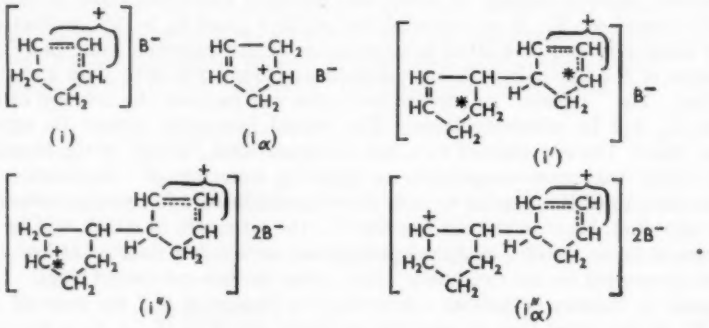
Retarders.—Added proton acceptors should compete with cyclopentadiene in reaction (I) for the proton derived from the acid, and retardation of the over-all reaction should result. The figures in Table 3 show that a number of basic solvents and ester (I), the product of the reaction, act as retarders. Rate equations for the formation of ester (I) or dicyclopentadiene, in the presence of retarders have been developed, but kinetic tests have not been carried out.

Proton Transfer to endo-*Dicyclopentadiene.*—It has been shown that the interaction of *endo*-dicyclopentadiene and trichloroacetic acid leads predominantly to trichloroacetate (Y) of *exo*-dihydrohydroxydicyclopentadiene, rather than to ester (I). Thus the velocity coefficient k_6 of the reaction:

$$\textit{endo}\text{-Dicyclopentadiene} + CCl_3{\cdot}CO_2H \xrightarrow{k_6} \text{ester (Y)} \qquad . \quad . \quad \textbf{(VI)}$$

is probably large compared with k_3'. Addition of trichloroacetic acid to *endo*-dicyclopentadiene must lead to the intermediate i' of reaction (III), according to the principle of microscopic reversibility: this, however, is without kinetic consequence because of the competitive reaction (VI), which occurs probably through an ion pair $C_{10}H_{13}^{+} \cdots B^{-}$ of a structure different from that of intermediate i'.

Structural Considerations.—Addition of a proton to cyclopentadiene leads to two ion pairs $C_5H_7^{+} \cdots B^{-}$, designated by i and i_α. It is assumed that i is preferentially formed, owing to resonance stabilisation. In reaction (II), i combines with cyclopentadiene, thereby forming the species $C_{10}H_{13}^{+} \cdots B^{-}$, which can exist in the form of three structural



isomers, one of which is i'. This is the only one which can be converted into *endo*-dicyclopentadiene by formation of a bond between the carbons marked by asterisks and removal of acid, without other rearrangements. The same ion pair, i', is assumed to participate in reaction (IV), in which the doubly charged ion pair $C_{10}H_{14}^{2+} \cdots 2B^{-}$ is formed. Five structural isomers of this are possible, but only in two of them, i'' and i''_α, is there resonance-stabilisation of the kind occurring in i', and for this reason the formation of isomers other than i'' and i''_α is not taken into account here. An inspection of models of i'' and i''_α shows that in the former intermediate the maximum distance between the two positively charged carbon atoms is larger; it is assumed, therefore, that i'' is more stable and is preferentially formed. This species can be simply converted into the observed product of the reaction, 3-(cyclopenta-2,4-dienyl)cyclopentyl trichloroacetate, by removal of one acid molecule, HB, and by combination of the remaining trichloroacetate counter-ion, B^{-}, with the carbon atom indicated by an asterisk. A similar reaction would convert the isomeric intermediate, i''_α, into the ester of 2-(cyclopenta-2,4-dienyl)cyclopentanol,

which is not formed under the specified conditions.[1] Thus the suggested mechanism accounts, not only for the formula [1] of the product, but also for the predominant formation of one of the possible structural isomers of the new bicyclopentyl derivatives.

Discussions, relating also to the two following papers, with Drs. C. H. Bamford and Y. Pocker are gratefully acknowledged.

WILLIAM RAMSAY AND RALPH FORSTER LABORATORIES,
UNIVERSITY COLLEGE,
GOWER ST., LONDON, W.C.1. [*Received, May 18th,* 1960.]

---

376. *Preparation and Properties of Deeply Coloured, Electrically Conducting Polymers.*

By P. V. FRENCH, L. ROUBINEK, and A. WASSERMANN.

Cyclopentadiene and four of its derivatives have been converted, under catalysis by trichloroacetic acid, into unsaturated polymers of molecular weight 1090—30,000, which are deeply coloured owing to the tail end of light-absorption peaks at 310—365 mμ and accept protons reversibly. The electronic spectra of the protonated polymers are characterised by peaks between 470 and 650 mμ. The equilibrium between these polymers and proton-donors has been studied and it has been shown, by measurements of electrical conductance, that the proton-transfer produces ion pairs; and the dissociation constants of these ion pairs have been determined. The electronic spectra and the proton-acceptor properties are explained by formation of a short and a longer sequence of conjugated double bonds.

IT has been reported [1] that 3-(cyclopenta-2,4-dienyl)cyclopentanol and its trichloroacetate can be converted into deeply coloured polymers. It is now shown that cyclopentadiene, cyclopentenyl chloride, cyclopentadienylidenecyclopentane, and a colourless cyclopentadiene polymer can be converted into deeply coloured species, all these reactions being catalysed by trichloroacetic acid in aprotic solvents. We prove in what follows that these polymers are highly unsaturated, containing a longer and a shorter sequence of conjugated double bonds, and we establish the end group of one of the polymers; the stoicheiometry of polymerisation, and the structure of reactive entities or repeating units, are discussed in the following paper.[2]

EXPERIMENTAL

Cyclopentadiene was purified and dried as described by one of us elsewhere.[3] 3-(Cyclopenta-2,4-dienyl)cyclopentanol,[1] cyclopentenyl chloride,[4] and cyclopentadienylidenecyclopentane [5] were redistilled shortly before use, and were stabilised by 10^{-4} mole of α-tocopherol per l.

Most solvents and acids were dried and refractionated or recrystallised shortly before use. Dodecylbenzenesulphonic acid was a sample in which the position of the dodecyl group relative to the other substituent is not known.

Preparation of Polymers.—The temperature and concentration conditions of the trichloroacetic acid-catalysed polymerisations are indicated in Table 1. After the specified times the free acid was removed with potassium hydrogen carbonate, the colour of the solutions changing from deep blue to red-brown. The polymers were isolated by precipitation with 10 volumes of

[1] Blakely, Gillespie, Roubinek, Wassermann, and White, *J.*, 1961, 1939.
[2] Murphy, Roubinek, and Wassermann, following paper.
[3] French, Ph.D. Thesis, London, 1958.
[4] Noeldechen, *Ber.*, 1900, **33**, 3348.
[5] Kohler and Kable, *J. Amer. Chem. Soc.*, 1935, **57**, 917.

XUM

ethanol, centrifugation, and drying *in vacuo*. Other precipitants for benzene, carbon tetrachloride, chloroform, carbon disulphide, or pyridine solutions are acetone, acetic acid, ether, and water. Some polymers were purified by repeated dissolution and precipitation or by chromatographic adsorption on calcium carbonate.

TABLE 1. *Preparation of deeply coloured polymers by trichloroacetic acid-catalysis in benzene, 0·001M with respect to α-tocopherol at 25°.*

Starting material (S.M.)	Initial concn. (mole/l.) S.M.	$CCl_3 \cdot CO_2H$	Reaction time (hr.)	Yield of polymer [a] (%)	Ref. design. of polymer
Cyclopentadiene	0·50—2·0	0·50—1·0	24	90	A
3-(Cyclopenta-2,4-dienyl)cyclopentanol	0·50	0·50	30—82	66	B
Cyclopentenyl chloride	1·0	0·50	16—113	27—28	C
Cyclopentadienylidenecyclopentane	0·50—1·0	0·50—1·0	18—22	63—75	D
Colourless cyclopentadiene polymer (E)	0·0017	1·0	25	70	F

[a] Calc. on starting material.

Comparing the oxygen and chlorine content of 3-(cyclopenta-2,4-dienyl)cyclopentanol and of cyclopentenyl chloride with the analyses of the relevant polymers (Table 2) indicates that respectively water and hydrochloric acid are released. This was directly proved by Karl Fischer titrations and by distilling the hydrochloric acid into traps containing standard alkali.

TABLE 2. *Analytical composition, molecular weights, bromine consumption, and viscosity number of polymers.*

Polymer	C (%)	H (%)	Cl (%)	O (%)	$10^{-3}M$	Br_2 (mol.)	$10^2[\eta]$ [d]
A	81·2 ± 0·2	7·91 ± 0·2	7·60 ± 0·3	3·3 ± 0·7	1·2 ± 0·2 [c]	15 ± 1	4·0 ± 0·3
A'	84·0 ± 0·3	8·60 ± 0·3	<0·3	9·4 ± 0·6 [b]	—	—	—
B	86·3 ± 0·3	8·43 ± 0·3	2·72 ± 0·3	2·5 ± 1·0	3·3 ± 0·1 [c]	36 ± 4	5·0 ± 0·3
C	83·9 ± 0·4	8·70 ± 0·3	6·70 ± 0·3	0·7 ± 1·0	1·09 ± 0·3 [c]	9 ± 1	3·5 ± 0·2
D	86·0 ± 0·3	8·70 ± 0·3	2·49 ± 0·4	2·8 ± 1·1	4·2 ± 0·1 [c]	45 ± 4	9·0 ± 0·4
E	83·8 ± 0·3	9·08 ± 0·3	6·42 ± 0·3	0·7 ± 0·9	32 ± 5 [d]	225 ± 30	10 ± 1
F	86·0 ± 0·3	8·68 ± 0·3	3·70 ± 0·3	1·6 ± 0·9	30 ± 5 [d]	290 ± 30	11 ± 1

[a] Polymer A' is the hydrolysis product of the ester polymer A. [b] The relatively high oxygen content is due to oxidation during alkaline hydrolysis and purification; these operations were carried out without antioxidant. [c] Number average. [d] Weight average. [e] In C_6H_6 at 25° (100 ml. of soln. per g.).

Polymer (E), the colourless starting material of polymer (F) (for reference designations see Table 1), was prepared from commercial stannic chloride [5a] (0·15 mole $l.^{-1}$) and cyclopentadiene (3·0 moles $l.^{-1}$) in chloroform containing α-tocopherol (0·0095 mole $l.^{-1}$). The stannic chloride was added dropwise, in 5 min., to the solution which was stirred at −5°; after 15 min. the temperature had risen to +6°; pyridine (0·3 mole $l.^{-1}$) was added, precipitating the stannic chloride as an adduct. This adduct was removed by centrifugation and the liquid was added to 10 volumes of ethanol; polymer E was thus precipitated and it was dried *in vacuo*.

Methods of Investigation.—The infrared absorption of polymer A was measured with a Perkin–Elmer instrument, for films and solutions in carbon tetrachloride, chloroform, and carbon disulphide, exposure to air being as short as possible.

Bromination and hydrogenation of the polymers were carried out by methods similar to those described elsewhere.[1,6]

Polymer solutions free from peroxides and air were prepared in a vacuum-vessel, V, fitted with a glass or plastic membrane tap,[6] sugar grease [7] being used in the former case. The starting materials were passed through a column of activated alumina, and the effluent was

[5a] Staudinger and Brusson, *Annalen*, 1926, **447**, 118.
[6] For details see Roubinek, Ph.D. Thesis, London, 1960.
[7] Meloche and Frederick, *J. Amer. Chem. Soc.*, 1932, **54**, 3264.

tested for peroxide;[8] if this was absent, the effluent, together with solvent, was placed in vessel, V, and, after removal of air at a pressure $<10^{-3}$ mm., dry, air-free trichloroacetic acid solution was added through a vacuum adaptor, W.[9] The acid solution had been prepared from a film of trichloroacetic acid, made *in vacuo*.[10]

For determination of the electronic spectra of polymers in absence of air, a vessel, V′, shown in Fig. 1 was used. After the side-arm had been filled by tilting, the vessel was introduced into a Unicam S.P. 500 spectrophotometer, without the vacuum's being released. Before the optical densities were measured, the solution in vessel V′ could be diluted with air-free acid solution which was transferred through an adaptor, W.

To remove free trichloroacetic acid in absence of air, the acid solution was transferred from vessel V, through adaptor W, into a second evacuated vessel, V″, containing dry, finely powdered potassium hydrogen carbonate, and the resulting potassium trichloroacetate was filtered off *in vacuo*.[10a] The filtrate was diluted with air-free solvent and transferred through adaptor W into vessel V′. The concentration of the final solution was estimated from the weights of

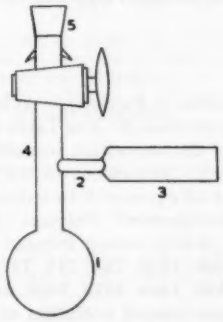


FIG. 1. *Apparatus.*

1, *Pyrex glass vessel*; 2, *graded seal*; 3, *silica light-absorption cell, path length* 0·102 *or* 0·700 *cm.*; 4, *position of restriction in glass tubing* (*see text*); 5, *connexion to vacuum-line.*

starting material, acid, solvent and acid-free filtrate. If the cyclopentadiene concentration was too low to be accurately determined by weighing, it was calculated from the weight of solvent and the volume of air-free cyclopentadiene vapour of known temperature and pressure. In these experiments, vessel V′ had a restriction at the position shown in the Fig. 1, where it was then sealed off *in vacuo*. In all these tests the optical densities of the solutions without polymer were separately determined.

A few electrical-conductance measurements in absence of air and peroxides were also carried out: the solution in vessel V was transferred, through the adaptor W, into the evacuated conductance cell, which permitted determination of the resistance, by a technique described previously,[11] without release of the vacuum.

The number average molecular weights of polymers (A)—(D) were measured ebullioscopically by means of an apparatus similar to that described by Ray,[12] usually with *p*-xylene as solvent. The weight average molecular weights of polymers (E) and (F) were deduced from measurements of the refractive-index increment and from light-scattering tests in benzene ($2{\cdot}00 \times 10^{-4}$M in α-tocopherol) carried out with a Rayleigh interferometer and a Brice–Phœnix light-scattering instrument. The latter instrument was calibrated according to directions of Brice, Halwer, and Speiser,[13] the results being checked with Ludox solution [14] and with a polystyrene of known molecular weight. Solutions and solvent were freed from dust by filtration into semioctagonal cells of known dimensions,[15] through dust-free, sintered-glass filters (porosity no. 5) under slight pressure. Filters, light-scattering cells, and pipettes were cleaned with dust-free acetone and kept in special containers. The dissymmetry measurements were corrected as described by

[8] Kharasch, *J. Amer. Chem. Soc.*, 1933, **55**, 2468.
[9] Cf. Fig. 3 of ref. 3.
[10] Wassermann, *J.*, 1959, 989.
[10a] Blakely, Ph.D. thesis, London, 1957.
[11] Wassermann, *J.*, 1954, 4329.
[12] Ray, *Trans. Faraday Soc.*, 1952, **48**, 809.
[13] Brice, Halwer, and Speiser, *J. Opt. Soc. Amer.*, 1950, **40**, 768.
[14] Kraut and Dandliker, *J. Polymer Sci.*, 1955, **18**, 563.
[15] Frank and Ullman, *J. Opt. Soc. Amer.*, 1955, **45**, 471.

XUM

Sheffer and Hyde.[16] For polymer (E), the Cabannes correction factor was also measured and found to be insignificant; this was also so for three similar polymers.[3]

In determining the ratios, R_{90}, R_{45}, and R_{135} of polymer (F), the influence of its colour had to be taken into account, by measuring the optical density of each solution used for light scattering and by applying the corrections of Brice, Nutting, and Halwer [17] and of Frank and Ullman.[15] Scattering tests with polymer E were carried out with light of 546 mμ in the range 0·6—5·7 g. of polymer per 100 ml. of solution, while polymer F was investigated with light of 578 mμ in the range 0·06—0·28 g./100 ml.; five concentrations were tested in each case. The refractive index increments (at 25°) of polymers E and F were respectively 0·0372 ± 0·005 (546 mμ) and 0·104 ± 0·006 cm.^{3} g.$^{-1}$ (578 mμ).

The equilibrium coefficients, K, in Table 5 and the electrical conductances were measured with freshly prepared solutions, which had been exposed to air as shortly as possible. Back-extrapolation [11] of optical densities and electrical resistance to the time of mixing were carried out in all cases. Prolonged exposure of the solution to air reduced the K values. Determination of optical densities above or below room temperature is described elsewhere.[2]

Results

Some Properties of Polymers.—At least three different batches of each polymer were prepared. The figures in columns 2—5 of Table 2 are means of analyses of each batch. The approximate temperature of decomposition was 200° for polymers (A), (A′), (B), (C), (D), and (E) and 100° for polymer (F). The colour of 0·1% benzene or chloroform solutions of these polymers is similar to that of aqueous 0·1N-iodine, but darkens when the solutions are shaken with acid or antimony trichloride.[6] Polymer (A) is amorphous, according to its X-ray powder diagram. This polymer showed strong infrared absorption peaks at 3021, 2920, 2890, 2860, 1773, 1695, 1577, 1366, 1260, 1251, 790, 741, 727, and 725 cm.$^{-1}$; medium and weak peaks were at 3640, 3620, 3570, 3436, 1464, 1073, 1000, and 910 cm.$^{-1}$. Heating polymer (A) at 350° in a stream of pure nitrogen caused evolution of carbon dioxide and hydrochloric acid, the dark brown solid residue being insoluble in benzene.

Polymer (A) is an ester of trichloroacetic acid, one mole of polymer containing one mole of trichloroacetate. This is proved by alkaline hydrolysis and is in accordance with the chlorine content. In isolating the alcoholic component (A′) of this polymer,[6] it was found that the only chlorine-containing product was potassium trichloroacetate, identified by conversion into its *S*-benzylthiouronium salt. The presence of the trichloroacetate groups in polymers (B) and (D) is made probable by their chlorine content and by the results of semiquantitative alkaline hydrolysis. The bromine consumption of polymer (A) (Table 2) agrees, within the limits of experimental error, with the results of catalytic hydrogenation.

The high degree of unsaturation of this polymer is confirmed by the following observations: 1 g. of polymer (A) was exposed for 9 months to dry air at 20°, the product (a) being extracted with hot dioxan; 0·034 mole of perbenzoic acid and 1 g. of polymer (A) in 190 ml. of benzene were left for 2 weeks at 7°, precipitation with light petroleum (b. p. 60—80°) then giving the product (b); ozone was bubbled for 20 hr. at 20° through a solution of 3 g. of polymer (A) in 100 ml. of carbon tetrachloride, thereby producing a precipitate (c). These faintly yellow or white products were centrifuged off, dried, and analysed, the yields being about 80% of the weight of the starting materials. Analysis indicated that the approximate average composition of the materials (a) and (b) is $(C_5H_6O)_x$ and that of material (c) is $(C_5H_6O_3)_x$. Degradation of the stable ozonide (c) with hydrogen peroxide was attempted, but crystalline materials could not be isolated.

Polymer (A) and maleic anhydride react with each other in benzene at 20°, to form a " co-polymer " of number average molecular weight 4300 ± 500, not a simple Diels–Alder adduct.[6]

Electronic Spectra.—These polymers are characterised by a light-absorption peak at 250—252 mμ and by a peak or shoulder between 310 and 365 mμ (Table 3). Here and below, molar light-absorption coefficients, ε, were calculated on the basis of the molecular weights given in Table 2. The colour of the polymers is due to the tail of one of the peaks or shoulders; $\lambda_{\frac{1}{2}}$ in Table 3 is the wavelength at which ε is one-half of the value listed in the sixth column. The

[16] Sheffer and Hyde, *Canad. J. Chem.*, 1952, **30**, 817.
[17] Brice, Nutting, and Halwer, *J. Amer. Chem. Soc.*, 1953, **75**, 824.

XUM

peaks in the spectrum of polymers (A), (B), and (D) could only be observed if peroxide and air were carefully excluded during preparation and measurement. Spectra of polymer (A) before and after exposure to air are shown in Figs. 2 and 3, similar effects being typical of all these polymers. The light-absorption peaks of polymers (C) and (F) could be detected in the presence of air for freshly prepared, relatively concentrated solutions, stabilised by α-tocopherol.

TABLE 3. *Electronic spectra of deeply coloured polymers at* 20°.

(sh = " shoulder "; the significance of $\lambda_{\frac{1}{2}}$ is explained in the text.)

		$\lambda_{max.}$ (mμ)		$10^{-3}\varepsilon$		$\lambda_{\frac{1}{2}}$
Polymer	Solvent [a]	(I)	(II)	(I)	(II)	(mμ)
A	Cyclohexane [b]	252	360	12 ± 1	5 ± 1	425
B	Cyclohexane [b]	251	310—320sh	106 ± 10	33 ± 3	355
C	Dioxan [c]	252	350	15 ± 1	10 ± 1	425
D	Cyclohexane [d]	250	~350sh	100 ± 10	26 ± 3	400
F	Cyclohexane [c]	254	365	78 ± 15	60 ± 15	480

[a] The polymerisation was carried out in carbon tetrachloride, an aliquot part being diluted with the solvents specified below, after completion of the reaction. Under the conditions of the optical-density measurements, the carbon tetrachloride concentration was sufficiently low to permit the detection of peak (I). [b] Air and peroxides excluded. [c] Air excluded. [d] Air present; solutions stabilised by α-tocopherol (0·002—0·005M); exposure to air as short as possible.

TABLE 4. *Electronic spectra of deeply coloured polymers in* M-*trichloroacetic acid at* 20°.

		λ (mμ)			$10^{-3}\varepsilon$		
Polymer	Solvent	(I)	(II)	(III)	(I)	(II)	(III)
A	C_6H_6 [b]	480(sh)	520	610	6·0 ± 1·0	7·4 ± 1·0	5·6 ± 1·0
	CCl_4 [b]	470	520(sh)	610	4·6 ± 1·0	3·3 ± 0·8	4·5 ± 1·0
B	C_6H_6 [c]	470(sh)	570(sh)	610	19 ± 1·0	30 ± 3	31 ± 1
	C_6H_6 [d]	480	580	—	14 ± 1	16 ± 1	—
	CCl_4 [c]	480	580	—	18 ± 2	25 ± 2	—
C	C_6H_6 [d]	480	510	625	7·0 ± 0·6	6·5 ± 0·6	7·4 ± 0·6
D	C_6H_6 [d]	480	580	—	21 ± 3	22 ± 3	—
	CCl_4 [c]	480	580(sh)	630	31 ± 4	15 ± 4	20 ± 3
F	Cyclohexane [d]	480	—	650	36 ± 10	—	60 ± 20
	C_6H_6 [d]	480	—	650	33 ± 10	—	50 ± 15
	CCl_4 [c]	475	603	653	21 ± 7	80 ± 25	70 ± 20

[b, c, d] See Table 3.

On addition of trichloroacetic acid, the polymers are converted into species the spectra of which are markedly altered, as shown in Fig. 3 and by the position of the peaks and shoulders in Table 4. The shape of these spectra depends on the acid concentration, up to ~1M, after which no further significant change occurs. This change is due to proton transfer from the acid to the polymer. The transfer is reversible, for if the free trichloroacetic acid is removed with potassium hydrogen carbonate in absence of air, the spectrum before addition of acid is restored. [If a benzene solution, 1·0M in trichloroacetic acid and 0·0010M in polymer (A), is exposed to air for 60 min. (rather than for the longer time mentioned in the legend of Fig. 3), the peaks of the spectrum are not destroyed, but one of them is shifted to 625 mμ, while the shoulder migrates to 560—570 mμ.] Beer–Lambert's law is obeyed in all these experiments. Polymer (A) was fractionally precipitated, thereby affording samples of number average molecular weights 947, 1012, 1083, 1088, 1300, and 1635, exposure to air being as short as possible. The spectra of these fractions in benzene, 1·0M with respect to trichloroacetic acid, were all similar to graph (b) in Fig. 3, there being no detectable trend of $\lambda_{max.}$ or $\varepsilon_{max.}$. Tests between 1000 and 2000 mμ with and without trichloroacetic acid were carried out, but no new peak due to electronic transitions was observed. The spectra of M-trichloroacetic acid solutions are characterised by tails stretching, in some cases, into the infrared range, as shown in Fig. 3; $\lambda_{\frac{1}{2}}$, the wavelength at which ε is one-half of the values listed in the last column of Table 4, is between 650 and 820 mμ. Attempts were made to find out whether the peak at 250—252 mμ (Table 3) occurs also with M-trichloroacetic acid solutions, but the results were inconclusive because the presence of acid prevented sufficiently accurate tests in this region.

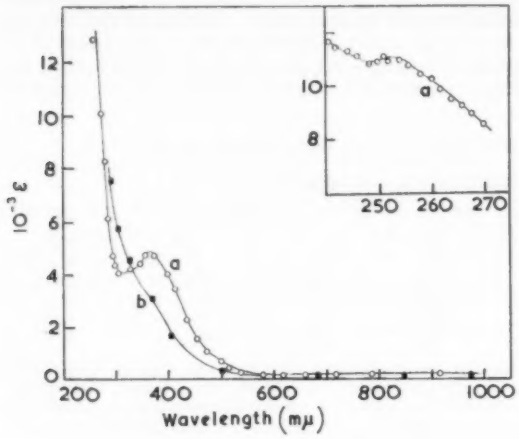


FIG. 2. *Electronic spectrum of polymer* (A), *at* 20°. *Solvents*: CCl_4 *for* 1000—480 mμ; *cyclohexane*–CCl_4 (0·729—0·360M *in* CCl_4) *for* 480—280 mμ.

Molarity of (A): $1{\cdot}24 \times 10^{-2}$—$7{\cdot}45 \times 10^{-4}$; *optical path length* 0·102 cm.

(a) *Oxygen and peroxides rigorously excluded.* (b) *The same solution exposed during* 70 hr. *to air of atmospheric pressure at* 20°.

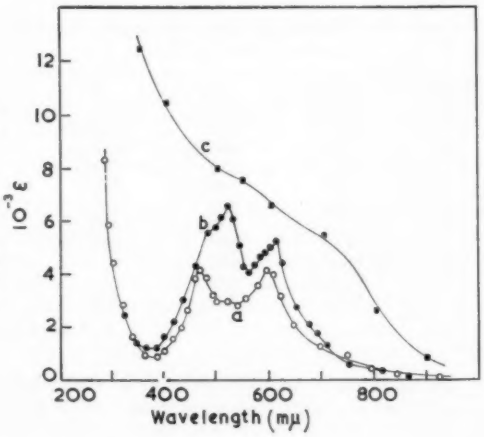


FIG. 3. *Electronic spectrum of polymer* (A) *in* 1·12M-*trichloroacetic acid at* 20°; *optical path length* 0·102 *cm.*

(a) *Solvent*: CCl_4; *molarity of polymer* (A) = $1{\cdot}95 \times 10^{-3}$ (O_2 *excluded*). (b) *Solvent*: C_6H_6; *molarity of polymer* (A) = $1{\cdot}10 \times 10^{-3}$ (O_2 *excluded*). (c) *Solvent*: CCl_4; *molarity of polymer* (A) *as in* (a); *the solution was originally free from molecular oxygen and peroxides, but had been exposed for* 240 *hr. to air of atmospheric pressure at* 20°.

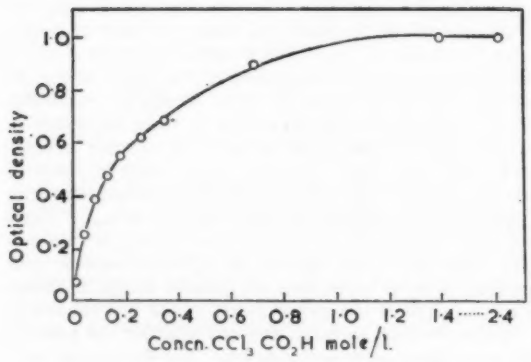


FIG. 4. *Optical density of polymer* (A) *in benzene at* 20°, *as a function of the trichloroacetic acid concentration. Polymer concn.* = $4{\cdot}14 \times 10^{-4}$ mole-l.; *optical path length* 0·516 cm.; 600 mμ; *optical densities extrapolated to the time of mixing.*

XUM

There is no peak between 470 and 260 mμ, the ε values increasing continually at wavelengths below 380 mμ.

The spectra of oxygen- and peroxide-free benzene solutions of polymer (A) (5×10^{-4}M) containing hydrochloric acid (0·3M), dodecylbenzenesulphonic acid (0·3M), or dichloroacetic acid (1·6M) are similar to those shown in Fig. 3a.

Proton-transfer Equilibria.—The reversible shift of the electronic spectra, in an aprotic solvent, on addition of trichloroacetic acid, is due to a proton transfer that produces ion pairs

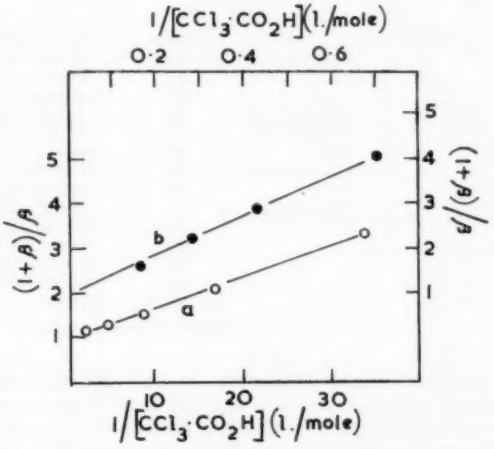


FIG. 5. *Relation between* $(1 + \beta)/\beta$ *and the reciprocal of the acid concentration; benzene; 20°. For definition of* β *see text.*

(a) *Polymer* (F) *and trichloroacetic acid; left ordinate, lower abscissæ; polymer concn.* $0{\cdot}124 \times 10^{-4}$ *and* $1{\cdot}24 \times 10^{-4}$M; $\lambda = 650$ mμ. (b) *Polymer* (A) *and dichloroacetic acid; right ordinate, upper abscissæ; polymer concn.* $2{\cdot}07 \times 10^{-4}$ *and* $4{\cdot}14 \times 10^{-4}$M; $\lambda = 470$ *and* 560 mμ.

in which the acid anion is firmly bound to the protonated polymer cation. If [P] is the concentration of the polymer not combined with acid, the ratio [Ion pair]/[P] = β can be deduced from

$$\beta = (d_A - d_0)/(d_\infty - d_A)$$

where d_A is the optical density of the polymer solution, containing acid of concentration [HA], d_0 is the optical density of the same solution without acid, and d_∞ is the optical density if [HA] is so high that practically complete protonation of the polymer occurs. Fig. 4 shows the results of typical experiments in which the optical density of a polymer solution as function of [HA] was determined, d_∞ being reached if [HA] is >1·4M. A knowledge of β enables one to compute the ratio:

$$[\text{Total polymer}]/[\text{Ion pair}] = (1 + \beta)/\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This is important because a plot of $(1 + \beta)/\beta$ against 1/[HA] is linear, in all the systems here considered, as shown for typical cases in Fig. 5. Such graphs can be extrapolated to 1/[HA] = 0, thereby obtaining the maximum number, m, of moles of acid bound by one mole of polymer. The intercepts of the graphs in Fig. 5 and the results of similar experiments show that m is 1·0 ± 0·1, and, therefore, the equilibrium coefficient, K, of the reversible reaction:

$$\text{Polymer} + \text{Acid} \rightleftharpoons \text{Ion pair} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

is represented by:

$$K = \frac{[\text{Ion pair}]}{[\text{Polymer}][\text{HA}]} \cdot \frac{f(\text{ion pair})}{f(\text{polymer}) \cdot f(\text{HA})} = \frac{\beta}{[\text{HA}]} \cdot f \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where f is the ratio of the three activity coefficients specified by the parentheses. It was found that in all cases log β is a linear function of log [HA], the slope of the graph being unity, within the limits of experimental error. (Similar observations were made with all other acids and polymers.) Thus f must be independent of [HA], within the concentration range of these experiments, and it is assumed, as a first approximation, that f is unity and that the equilibrium

coefficient, K, can be computed from the intercept of the log β–log [HA] graphs. Most of the K values in Table 5 were determined in this manner, except those in lines 7 and 8, which were calculated by Page's method,[18] without a knowledge of d_∞. The equilibrium coefficient in line 5 was calculated on the assumption that the d_∞ values of mono- and di-chloroacetic acid are equal; an experimental determination of the former value is not possible, because of the limited

TABLE 5. *Equilibrium coefficient, K, of proton-transfer to deeply coloured polymers, in benzene (except as specified).*

Polymer	Acid	Temp.	Concn. range: Acid (mole/l.)	Concn. range: Polymer (g./l.)	K (l./mole)
A	$CCl_2{\cdot}CO_2H$	15°	0·105—2·10	0·370	4·3 ± 0·5
A	,,	25	0·0435—2·44	0·0620—0·748	6·1 ± 0·5
A	,,	37	0·104—1·74	0·374	6·5 ± 0·5
A	$CHCl_2{\cdot}CO_2H$	25	0·155—3·48	0·0748—0·848	0·65 ± 0·1
A	$CH_2Cl{\cdot}CO_2H$	25	0·325—1·56	0·490—1·99	0·061 ± 0·02
A	HCl	20	0·00414—0·0414	0·134	25 ± 4
A	$C_6H_4R{\cdot}SO_3H$ [a]	20	0·0212—0·170	0·134	17 ± 4
A	Picric	20	0·0440—0·146	0·134	10 ± 3
A	$CCl_3{\cdot}CO_2H$	20	0·202—2·00	0·0239—0·239	3·0 ± 0·5 [b]
A′	,,	20	0·0440—2·44	0·0500	8 ± 2
B	,,	20	0·0313—1·74	0·115—1·15	6·3 ± 1
C	,,	20	0·0150—2·00	0·206 ± 2·06	11 ± 2
D	,,	20	0·0600—2·89	0·228—2·28	4·0 ± 1
F	,,	20	0·0300—1·50	0·572—5·72	14 ± 2

[a] Dodecylbenzenesulphonic acid. [b] In $CHCl_3$.

solubility of monochloroacetic acid and its relatively low acidity. Plotting the logarithm of the K values in lines 2, 4, and 5 of Table 5 against the logarithm of the dissociation constants, expressed in mole/l., of the three chloroacetic acids in water gave a linear functional relationship of the Brönsted type with the parameters 0·50 ± 0·2 and 1·5 ± 0·3.

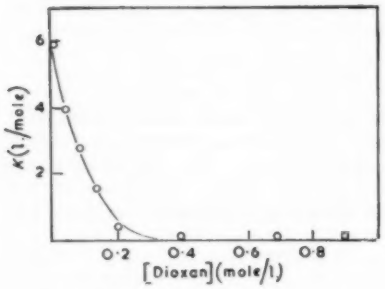


FIG. 6. *Influence of the basic solvent dioxan on the equilibrium coefficient, K, relating to polymer* (A) *and trichloroacetic acid; benzene solution; 20°. Concentration of polymer and acid respectively* 3·88 × 10^{-4}M *and* 0·140—1·95M.

If a benzene solution, 4·0 × 10^{-4}M in polymer (A) and 0·140M in trichloroacetic acid, is made 0·040M with respect to piperidinium trichloroacetate, or 2·0M with respect to ethanol or acetone, the equilibrium coefficient, K, decreases to respectively 2·0 and <0·1 l. mole^{-1}. Fig. 6 shows similar effects with dioxan. In all these experiments β was calculated on the assumption that d_∞ is not altered by added substances.

Electrical Conductance.—The specific electrical conductance, κ, of a benzene solution 1·00M in trichloroacetic acid or 0·0500M in polymer (A) at 25° is respectively $<10^{-10}$ or $<10^{12}$ Ω^{-1} cm.$^{-1}$; if, however, the solution contains both the acid and the polymer, κ is 2·40 × 10^{-7} Ω^{-1} cm.$^{-1}$. Similar effects, observed with five other proton donors and with polymers B—F, are due to ion pairs formed in reaction (3). The ion-pair concentration, c', can be calculated, if one knows the equilibrium constant, K, of equation (4) and the stoicheiometric polymer concentration. The molar conductance, Λ, of the ion pairs is defined by:

$$\Lambda = (\kappa_{ev} - \kappa_{acid})/c' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

[18] Page, *Trans. Faraday Soc.*, 1953, **49**, 637.

where κ_{ov} and κ_{acid} are respectively the over-all specific conductance of the solution and the specific conductance of the solution containing acid without polymer. In most tests κ_{acid} was less than 0·15 κ_{ov}. The ion pairs, $^+PH \cdots Anion^-$, dissociate, at sufficiently low concentration, according to:

$$^+PH \cdots Anion^- \overset{K_d}{\rightleftharpoons} PH^+ + Anion^- \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

the polymer cation, PH^+, and the acid anion being regarded as carriers of the electrical current; K_d, the dissociation constant of the binary ion pairs, is defined by:

$$K_d = \frac{[PH^+][Anion^-]}{[^+PH \cdots Anion^-]} \cdot \frac{f(PH^+) \cdot f(Anion^-)}{f(^+PH \cdots Anion^-)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where the f's are activity coefficients. If we assume, as a first approximation, that the ratio of the f's is unity and that the dissociation of the acid in benzene is not significant,[10] it follows from equation (7) that:

$$\log \Lambda = - \log c' + \tfrac{1}{2}(\log K_d + 2 \log \Lambda_0) \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where Λ_0 is the molar conductance extrapolated to $c' = 0$. In all experiments with these

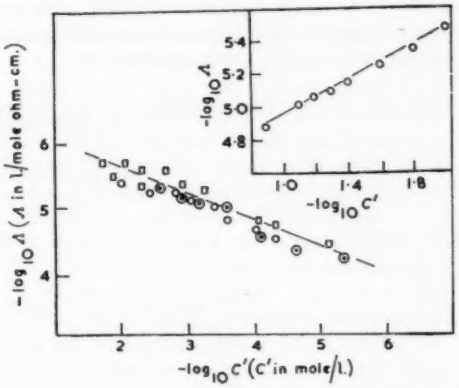


FIG. 7. *Relation between logarithm of molar electrical conductance* (Λ *in l. mole*$^{-1}$ *ohm*$^{-1}$ *cm.*$^{-1}$) *and logarithm of ion-pair concentrations, c'* (*mole l.*$^{-1}$). *The ion-pairs are formed by proton-transfer to polymer* (A); *benzene*; 25·0°. ○, □, *and* ⊙ *relate to tri-, di-, and mono-chloroacetic acid respectively as proton-donors.*

polymers a linear relation between log Λ and log c' with slope 0·50 ± 0·05 is observed, provided the ion-pair concentration is in the range given in the fourth column of Table 6. Typical graphs of this kind are on the left-hand side of Fig. 7. The ion-pair dissociation constant, K_d,

TABLE 6. *Results of electrical conductance measurements in benzene at* 25·0°.

K_d is the dissociation constant of binary ion pairs formed by proton-transfer to deeply coloured polymers. c' = concn. of ion pairs in mole/l. Λ in mole^{-1} Ω^{-1} cm.$^{-1}$ l.

Polymer	Acid	Concn. of acid (mole/l.)	Range of $-\log_{10} c'$	No. of c' values tested	$-\log_{10}\Lambda$ for $c' = 10^{-3}$ mole/l.	$-\log_{10}\Lambda_0$	$-\log_{10} K_d$ (K_d in (mole/l.)
A	$CCl_3 \cdot CO_2H$	1·00	2·0—4·3	15	5·20 ± 0·10	3·0 ± 0·5	6·8 ± 1·0
	$CHCl_2 \cdot CO_2H$	1·00	1·7—5·1	13	5·20 ± 0·10	3·0 ± 0·5	7·2 ± 1·5
	$CH_2Cl \cdot CO_2H$	0·946	2·6—5·4	7	5·20 ± 0·10	3·0 ± 0·5	6·8 ± 1·5
	Picric	0·127	1·7—3·5	4	6·75 ± 0·10	5·0 ± 1·0	6·6 ± 2·5
	$C_6H_4R \cdot SO_3H$ [a]	0·256	2·1—3·5	3	4·80 ± 0·10	3·5 ± 0·5	5·4 ± 2·0
B	$CCl_3 \cdot CO_2H$	1·00	2·9—6·4	9	4·50 ± 0·10	2·9 ± 0·2	5·8 ± 1·0
C	,,	1·00	1·8—4·8	4	5·20 ± 0·10	3·5 ± 0·5	5·8 ± 1·8
D	,,	1·00	2·6—7·9	8	4·90 ± 0·10	2·0 ± 0·5	8·6 ± 1·5
F	,,	1·00	3·6—4·6	4	4·70 ± 0·10	3·0 ± 0·5	6·4 ± 1·0

[a] Dodecylbenzenesulphonic acid.

can be determined by extrapolation to $-\log c' = 0$, thereby obtaining the intercept $i = \frac{1}{2}(\log K_d + 2 \log \Lambda_0)$, the limiting molar conductance being derived by the method used previously.[10] The results of the electrical conductance measurements are in Table 6. On the whole, the K_d

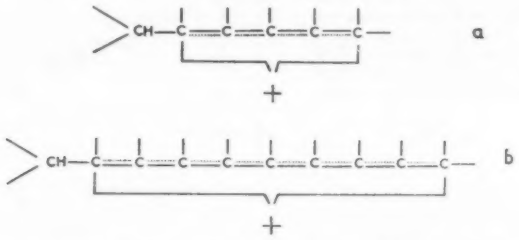
values are larger than those of binary ion pairs formed by proton-transfer to authentic conjugated polyenes.[19] In order to see, in one case, whether Λ_0 is correct and whether the assumption regarding the activity coefficient ratio in equation (7) is justified, K_d was calculated for the ion-pair formed from polymer (A) and trichloroacetic acid, with the help of a convergent extrapolation method.[18,19] The value so obtained agreed with that in the first line of the last column of Table 6.

The graph on the right-hand side of Fig. 7 shows that the molar conductance of the ion-pairs formed from trichloroacetic acid and polymer (A) increases with increasing concentration, if c' is larger than about 0·01M. The conductance minimum must be due to the influence of triple ions which are formed in the specified concentration range.[20] Tests with other polymers or acids in a similar concentration range have not been carried out.

Discussion

Polymer (A).—Bromination, hydrogenation, and oxidation (p. 1956 and Table 2) show that there are 15 ± 1 double bonds per mole of polymer. Some of these double bonds must be conjugated, the two peaks of the electronic spectrum (see Fig. 2) being assigned to a sequence of respectively 2—3 and 4—6 conjugated double bonds. The numbers are estimated by comparison with electronic spectra of reference polyenes.[21] The experiments described in this paper do not enable one to decide whether this polymer contains also isolated double bonds, but other considerations [2] seem to indicate that both conjugated and isolated double bonds are formed.

Fig. 8. *Chromophores formed by "end-on" proton-transfer to a sequence of three or five conjugated double bonds in polymer* (A).



The presence of conjugated double bonds is confirmed by the observed proton-acceptor properties. As in the case of authentic conjugated polyenes,[10,11,22] a Brönsted-type relation has been observed (p. 1960), the dissociation constants, K_d, of binary ion pairs formed by protonation are much larger than the K_d values of substituted ammonium salts in the same solvent,[23] and the electronic spectra of the protonated species are shifted to longer wavelength. It has been shown that only one mole of proton-donor reacts with one mole of polymer and it follows that either the short or the long sequence of conjugated double bonds is protonated. If the shorter sequence consists of three double bonds, and if the proton is transferred to the end of the conjugated system, as in authentic conjugated polyenes,[24] a chromophore shown in Fig. 8a would be produced. In attempting to find out whether this can give rise to an electronic spectrum with peaks between 470 and 610

[19] Fuoss and Kraus, *J. Amer. Chem. Soc.*, 1933, **55**, 476.
[20] For triple-ion formation in solvents of low dielectric constant see Fuoss and Kraus, *J. Amer. Chem. Soc.*, 1933, **55**, 2387, 3614; Hughes, Ingold, Patai, and Pocker, *J.*, 1957, 1206.
[21] Barrany, Braude, and Pianka, *J.*, 1949, 1898; Euler, Karrer, Klussmann, and Morf, *Helv. Chim. Acta*, 1932, **15**, 502; Karrer and Benz, *ibid.*, 1948, **31**, 1907; Kuhn, *Z. angew. Chem.*, 1937, **50**, 705; Karrer and Jucker, "Carotinoide," Birkhäuser, Basle, 1948, pp. 140, 200, 365; Smakula, *Z. angew. Chem.*, 1934, **47**, 664; Karrer, Eugster, and Faust, *Helv. Chim. Acta*, 1951, **34**, 823; Karrer and Leumann, *ibid.*, p. 445.
[22] Wassermann, *J.*, 1959, 983.
[23] Cf. Roubinek, Ph.D. Thesis, London, 1960, Appendix 5.
[24] Wassermann, (*a*) *J.*, 1959, 979; (*b*) *J.*, 1960, 891; *Mol. Phys.*, 1959, **2**, 226.

mμ (see Fig. 3 and Table 4) a simple free-electron treatment [25] of the spectra of mesomeric ions is used from which it follows that:

$$1/\lambda_1 = (V_0 - hc)(1 - 1/N) + (h/8mc)(N + 1)/L^2 \quad . \quad . \quad . \quad (9)$$

where λ_1 is the wavelength of the peak, V_0 is the amplitude of a one-dimensional potential operating on the π-electrons, L is the chromophore length, computed from standard bond distances,[22,24,25] h is Plank's constant, c is the velocity of light, m is the mass of the electron, and N is Avogadro's number. The V_0 values of previously investigated conjugated polyenes [22,24a] varied between 5·3 and 44·5 kcal./mole; in attempting to estimate an upper limit of λ_1 corresponding to the chromophore shown in Fig. 8a, it is assumed that V_0 is 5·3 kcal./mole, whence λ_1 equals 334 mμ. The electronic spectrum of protonated polymer (A) does not show peaks below 470 mμ and it is concluded that the short sequence of conjugated double bonds is not protonated. It follows that the observed effects are due to proton-transfer to the longer sequence; if this contains five * conjugated double bonds, " end-on " protonation would produce the chromophore shown in Fig. 8b. Computing the length L in equation (9) as before,[22,24a] and taking the experimental value of 610 mμ for λ_1, it follows that V_0 is 8·0 kcal./mole. This is reasonable, as shown by comparison with the results of a similar calculation [22] relating to protonated vitamin-A acetate, which also contains five conjugated double bonds.

Polymers (B), (C), (D), *and* (F).—The electronic spectra are somewhat similar to those of polymer (A), and it is probable that the peaks at 250—252 mμ and the peaks or shoulder between 310 and 365 mμ are also brought about by a short and a long sequence of conjugated double bonds. All these polymers are reversible proton-acceptors; the spectra of the protonated species are compatible with the supposition that in all cases the longer sequence of conjugated double bonds reacts with the acid. Confirmation is provided by the equilibrium constants, K, and the ion-pair dissociation constants, K_d, which are of the same order of magnitude as the relevant constants of polymer A.

In the case of free-draining linear-coiling or linear rod-shaped polymers of different molecular weight, M, but comparable chemical structure, the exponent in the relationship, viscosity number ($[\eta]$) = constant × M^{α}, is either about unity or larger. For four of the five polymers listed in Table 2 log $[\eta]$ is a linear function of log M, within the limits of the experimental error specified. The slope α of the log $[\eta]$–log M graph is 0·39 ± 0·07. It could be suggested that this small α value indicates that these polymers are not free-draining linear species, but this is improbable in view of the small M values. It has been observed [26] that non-linear polymers are characterised by small α values and therefore it is reasonable to assume that the polymers here considered are also non-linear species.

Alternative Interpretation of the Electronic Spectra.—It could be suggested that the double bonds in these polymers are all conjugated and that the observed peaks of the electronic spectra are due to the superposition of the spectra of the various homologues. This, however, is difficult to reconcile [2] with the molecular-weight distribution of polymer A and with the absence of significant influence by the molecular weight on the position of the peaks listed in column 3, and in lines 1, 3, and 5 of column 4, in Table 3.

We are grateful to the Ministry of Education and to the Czech Refugee Trust Fund for grants (to P. V. F. and L. R.), to Mr. H. M. Hutchinson and Dr. K. Lawrence (Distillers Co. Ltd.) for the determination of the molecular weights of polymers B, C, and D, to Dr. R. Schnurmann (Esso Co.) for the infrared spectrum of polymer (A), and to Dr. A. Davies for helpful discussions.

WILLIAM RAMSAY AND RALPH FORSTER LABORATORIES,
UNIVERSITY COLLEGE, GOWER STREET, LONDON, W.C.1. [*Received, May 18th,* 1960.]

* This figure, rather than four or six, has been chosen, in view of the proposed mechanism of polymerisation.[2]

[25] Kuhn, *J. Chem. Phys.*, 1949, **17**, 1198.
[26] Zimm and Stockmeyer, *J. Chem. Phys.*, 1949, **17**, 1301; Stockmeyer and Fixman, *Ann. New York Acad. Sci.*, 1953, **57**, 334; Kilb, *J. Polymer Sci.*, 1959, **38**, 403.

XUM

377. *Mechanism of Formation of a Deeply Coloured Electrically Conducting Polymer.*

By J. Murphy, L. Roubinek, and A. Wassermann.

3-(Cyclopenta-2,4-dienyl)cyclopentyl trichloroacetate (I) can be converted into the same polymer (A) as is obtained from cyclopentadiene. This is due to the occurrence of two consecutive reactions, the first leading from cyclopentadiene to the ester (I), and the second, slower reaction, giving polymer (A). A kinetic investigation of this polymerisation has been carried out and the degree (n) of polymerisation under different conditions determined. The results are compatible with proton-transfer in the initiation and incorporation of the ester (I) into growing carbonium-ion pairs during propagation and termination. It is suggested that all steps involve hydrogen shifts and that propagation and termination are accompanied by elimination of trichloroacetic acid. This mechanism accounts for the observed kinetics and n values, and for the formation of non-linear species containing a short and a long sequence of conjugated double bonds.

The preceding paper [1] describes trichloroacetic acid-catalysed reactions of substances containing endocyclic double bonds in five-membered rings, which lead to deeply coloured polymers of unusual properties. An attempt is now made to elucidate the mechanism of one of these polymerisations. The formation of one polymer, termed (A),[1] was selected for study because the starting material, cyclopentadiene, is easily available and because this polymer has been more extensively investigated than the other products.

This paper deals with the stoicheiometry of the polymerisation which is formally, but not kinetically, a polycondensation, with the degree and rate of polymerisation, and with oxidative degradation. A detail of general interest is a method of calculus used for solution of a differential rate equation relating to two consecutive reactions.

Experimental

The preparation of 3-(cyclopenta-2,4-dienyl)cyclopentyltrichloroacetate (I), the purification of trichloroacetic acid, cyclopentadiene, solvents, and added substances, removal of traces of peroxides, optical density measurements in absence of atmospheric oxygen, electrical conductance measurements and electrometric titrations have been described elsewhere.[1-6] Spectrophotometric and conductometric measurements showed that the ester (I) contained less than 2% of polymer (A). The equivalent weight of the ester was always somewhat lower than the theoretical value, owing to the presence of free acid, probably trichloroacetic acid (cf. below). The term N_E in equation (5) (below) is the sum of the number of moles of ester (I) and of free acid. In measuring the rate of polymerisation of ester (I), by titrating liberated trichloroacetic acid, a correction was made for the free acid present in the ester at the start of the run. Titrations of liberated acid were carried out in benzene–ethanol or carbon tetrachloride–ethanol with indicators,[2-4,6] or electrometrically [1,6] if the solution was intensely coloured. In most experiments alcoholic potassium hydroxide was used, an excess of alkali being avoided. Control experiments with isopentylamine in benzene showed that the unused ester was not thus hydrolysed. Back-titrations were carried out with trichloroacetic acid in benzene.

In one set of measurements, a mixture was made of (*a*) the ester (I), previously shaken with barium oxide for several days, (*b*) benzene previously refluxed with potassium, and (*c*)

[1] French, Roubinek, and Wassermann, preceding paper.
[2] Blakely, Gillespie, Roubinek, Wassermann, and White, *J.*, 1961 1939.
[3] Blakely, Ph.D. Thesis, London, 1957.
[4] French, Ph.D. Thesis, London, 1958.
[5] Wassermann, *J.*, 1954, 4329; 1959, 986.
[6] Roubinek, Ph.D. Thesis, London, 1960.

trichloroacetic acid, prepared from a film *in vacuo* [5] and dried for several hours at 40°/1 mm. over phosphorus pentoxide. This mixture was made in absence of atmospheric moisture, greaseless taps [1] being used, and the solution was filled into dry glass vessels; these were sealed off *in vacuo* and introduced into a thermostat bath. The rate coefficients obtained agreed to within the experimental error (±10%) with those determined in runs carried out in presence of atmospheric moisture. Solutions did not come into contact with taps coated with sugar grease,[1] because this retards the rate of polymerisation. In connexion with rate coefficients deduced from optical-density measurements, some experiments were done in which the optical cell [7] was sealed *in vacuo* and placed into a double-walled thermostat housing which fitted into the cell compartment of a Unicam S.P. 500 spectrophotometer.

The electronic spectra and specific electrical conductance, κ, of two sets of benzene solutions were determined: (*a*) final reaction mixtures obtained from ester (I) and trichloroacetic acid; (*b*) solutions containing known quantities of trichloroacetic acid and polymer (A), which had

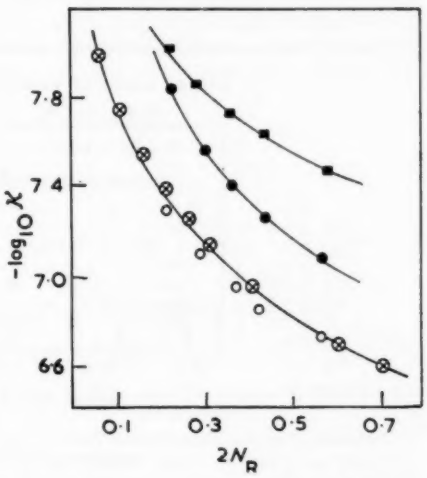


FIG. 1. *Relations between specific electrical conductance, κ (in ohm^{-1} cm.$^{-1}$), and $2N_R$ (for definition of N_R see text); benzene solution at 25°.* [$CCl_3{\cdot}CO_2H$] = ■ 0·250, ● 0·500, ⊗ 1·50, ○ 2·00 *mole l.*$^{-1}$.

been purified as described before.[1] The positions of the light-absorption peaks,[8] optical densities and κ values agreed to within the limits of experimental error (±5%) if the concentrations of solutions (*b*) were adjusted so that they coincided with those of solutions (*a*) on the assumption that there had been 100% conversion of starting material into polymer (A).

Conversion of ester (I) into polymer (A) under catalysis by trichloroacetic acid is accompanied by a gradual increase of the specific electrical conductivity, κ, until the limiting value [1] corresponding to complete polymerisation is reached. Fig. 1 shows the relation between log κ and N'_R, the number of C_{10} residues per l. of solution incorporated in polymer (A). Separate experiments with fractionated polymers of number-average molecular weight, M_n, in the range 844—1635 showed that the log κ–$\frac{1}{4}N'_R$ relations are independent of M_n, within an accuracy of about 10%.

RESULTS

Stoicheiometry.—The bimolecular dimerisation of cyclopentadiene occurs at 25° simultaneously with the catalysed dimerisation [9] if the reaction mixture contains >0·2M-trichloroacetic acid. If the acid concentration is higher, *e.g.*, 0·5M, both the bimolecular and the catalysed dimerisation are overshadowed by a reaction leading to ester (I).[2,10] This ester, however, could only be isolated [2] if the reaction time was relatively short: after longer times,

[7] Fig. 1 of ref. 1.
[8] Fig. 3 of ref. 1.
[9] Rubin, Steiner, and Wassermann, *J.*, 1949, 3046.
[10] Blakely and Wassermann, *J.*, 1961, 1946.

XUM

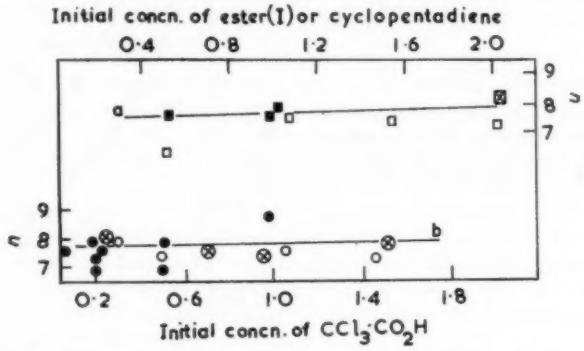
polymer (A) was the major product.[1] These observations indicate that the following two consecutive reactions occur:

$$2C_5H_6 + HB \xrightarrow{HB} C_{10}H_{13}B \quad . . . . . (1)$$

$$nC_{10}H_{13}B \xrightarrow{HB} R_nB + (n-1)HB \quad . . . . . (2)$$

where HB, $C_{10}H_{13}B$, R, and B are respectively symbols for trichloroacetic acid, ester (I), C_{10} and trichloroacetate residues incorporated into polymer (A). Trichloroacetic acid is a reactant in (1), a product in (2), and a catalyst in both processes; the mechanism of the catalysis of reaction (1) has already been discussed,[10] and that of (2) will be dealt with below. Many experiments confirmed that the same polymer (A) is obtained from cyclopentadiene as from isolated ester (I), as established by the analytical composition, unsaturation, molecular and equivalent weight, electronic spectrum, and electrical conductance of the products. The results of one set of such experiments are in Fig. 2. A typical run in which polymer (A) was

FIG. 2. *Number-average degree of polymerisation, n, of polymer* (A); *benzene solution at* 25°.



Influence of initial concentrations (mole $l.^{-1}$) *of ester* (I) *or cyclopentadiene* (*upper abscissæ*) *and trichloroacetic acid* (*lower abscissæ*).

□ ■ ☒ *relate to upper abscissæ and right-hand ordinate.* [*In these experiments the initial concentration of cyclopentadiene or of ester* (I) *was varied.*]

○ ⊗ ● *relate to lower abscissæ and left-hand ordinate.* [*In these experiments the initial concentration of trichloroacetic acid was varied.*]

■ *and* ●: *Conversion of isolated ester* (I) *into polymer* (A) *in presence of air. Initial concn.: trichloroacetic acid,* 0·198—0·205M *for* ■; *ester* (I) 0·388—0·477M *for* ●.

□, ☒, ○, *and* ⊗: *Conversion of cyclopentadiene into polymer* (A) *without isolation of ester* (I). □ *and* ○, *in presence of air;* ☒ *and* ⊗, *in absence of air. Initial concn.: trichloroacetic acid,* 0·994—1·04M *for* □ *and* ☒; *cyclopentadiene* 0·921—1·10M *for* ○ *and* ⊗.

prepared from the isolated ester (I) was as follows: a dry benzene solution, 0·51M with respect to ester (I), 0·203M with respect to trichloroacetic acid, and about 10^{-3}M with respect to the antioxidant α-tocopherol, was left for 23 hr. at 25°; then the deep blue solution was shaken with an excess of solid potassium hydrogen carbonate to remove free acid. After filtration, polymer (A) was isolated as described before; [1] the yield was over 90%.

Number-average Degree of Polymerisation, n, of Polymer (A).—This is defined by:

$$n = (M_n - 163{\cdot}4)/132{\cdot}1 \quad . . . . . (3)$$

where M_n is the number-average molecular weight. Polymer (A) is an ester of trichloroacetic acid,[1] the number-average equivalent weight of which equals M_n; [1] thus n can be calculated from

$$n = N_R^{\infty}/(N_A^{\circ} - N_A^{\infty}) \quad . . . . . (4)$$

$$n = N_R^{\infty}/(N_E^{\circ} + N_A^{\circ} - N_A^{\infty}) \quad . . . . . (5)$$

where N_R, N_E, and N_A are the number of moles per kg. of solution of, respectively, C_{10} residues incorporated in the polymer, trichloroacetate in ester (I) (corrected for initial free acid), and trichloroacetic acid. The superscripts ° and ∞ indicate that the relevant quantities relate to zero time or to the end of polymerisation; equations (4) and (5) were applied to results of experiments in which the starting material was, respectively, cyclopentadiene and ester (I). N_R was assumed to equal $\frac{1}{2}N_0^\circ$, where N_0° is the number of moles of cyclopentadiene or C_5 residues in ester (I). This mode of computation is justified by experiments described on p. 1965, which showed that the polymerisation is practically complete. N_E and N_A were determined by electrometric titration of weighed quantities of solution, with an accuracy of ±0·2%; N_A^∞ was determined 10 hr. after the start of the polymerisation. After the determination of N_A^∞, an excess of 0·1N-alcoholic potassium hydroxide was added to the neutral reaction mixture; the alkaline solution was left for several hours at 25°, polymer (A) being completely hydrolysed. Back-titration showed that the number of moles of potassium hydroxide consumed, per kg. of solution, agreed to within ±10% with $N_A^\circ - N_A^\infty$ or with $N_E^\circ + N_A^\circ - N_A^\infty$. These results relate to polymers in the final reaction mixture; the *n*-values of precipitated polymers are somewhat higher, owing to greater solubility of homologues of low molecular weight.

Fig. 2 shows the results of a series of measurements in benzene at 25°; *n* values determined under different conditions are in Table 1. There appears not to be significant influence by

TABLE 1. *Number-average degree of polymerisation, n, of polymer* (A) *prepared under different conditions.*

Solvent	Temp.	Initial concn. (mole/l.) ester (I)	$CCl_3{\cdot}CO_2H$	*n*
C_6H_6	10°	0·513	0·500	6·0 ± 0·6
	25	0·500—1·00 *	0·0500—0·95 *	7·0 ± 0·7
	35	0·513	0·0500	10 ± 1
CCl_4	10	0·513	0·432	6·0 ± 0·6
	25	0·128—1·08	0·203—0·219	7·0 ± 0·7
	35	0·513	0·200	10 ± 1
C_6H_6; 3·0M in $PhNO_2$	25	0·505	0·200	12 ± 2
C_6H_6; 0·3M in dioxan	25	0·300—0·900	0·200—0·400	7·0 ± 1·0

* Cf. Fig. 2. In one of these experiments the initial reaction mixture was made 0·024M with respect to polymer (A): there was no significant change in *n* of the final polymer.

initial concentration of cyclopentadiene, ester (I), trichloroacetic acid, or molecular oxygen. In all these experiments, *n* was measured at the end of reaction. Attempts were made to precipitate polymer (A) before reaction (2) had gone to completion, and to determine *n* of the precipitated material: the results were not reliable, possibly owing to occlusion or adsorption of unchanged ester (I)—the separation was made difficult by colloid chemical effects that will be described elsewhere. It could nevertheless be shown (see p. 1968) that *n* does not change between about 20% and 100% conversion.

Rate of Trichloroacetic Acid-catalysed Polymerisation of Ester (I).—This is represented by:

$$dy/dt = k(a - y)(b + y - y/n) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where *a* and *b* are the initial concentration of ester (I) and trichloroacetic acid, *n* is the number-average degree of polymerisation, and *k* is the rate coefficient. Integration leads to

$$k = \frac{2{\cdot}30}{(b + \lambda' a)t}\left\{\log_{10}\left(\frac{a}{a - y}\right) + \log_{10}\left(\frac{b + \lambda' y}{b}\right)\right\} \quad . \quad . \quad . \quad . \quad (7)$$

where $\lambda' = (n - 1)/n$ is assumed to be constant (cf. below). For the special case $b \gg a$ one obtains:

$$k = \frac{2{\cdot}30}{bt}\log_{10}\left(\frac{a}{a - y}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The concentration (*y*) of converted ester (I), was determined colorimetrically (the product being deeply coloured) or by titrating the liberated trichloroacetic acid; the latter method is,

XUM

however, only applicable if b is not much larger than a. In some experiments an aliquot part of the reaction mixture was f times diluted (10—50-fold) with M-trichloroacetic acid in benzene, and the optical density, α, of the diluted solution was measured in a cell of optical path length 0·0944 cm. at a wavelength close to one of the absorption peaks.[9] The time dependence of α was measured for the diluted solution and graphical back-extrapolation to the time of dilution was carried out. The first α values were measured about 2 min. after dilution. In other experiments atmospheric oxygen was excluded throughout, the optical density of the undiluted reaction mixture being determined after times t and t', thereby permitting computation of the velocity coefficient by Guggenheim's method.[11] In the experiments involving the titration by liberated ester, y was calculated from:

$$y = [n/(n-1)]A_t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where n is the number-average degree of polymerisation and A_t is the acid concentration in excess of that added at zero time and corrected as indicated above. Results of such rate measurements in benzene, at 25°, are in Fig. 3, which shows that k does not depend significantly on the initial concentration.* Rate coefficients were also determined under other conditions,

TABLE 2. *Velocity coefficients, k, of conversion of ester* (I) *into polymer* (A). *Summary of results.*

Temp.	Added substance (mole l.$^{-1}$)	10^3k (l. mole^{-1} min.$^{-1}$)	Added substance (mole l.$^{-1}$)	Retardation (%)	Temp.	10^3k (l. mole^{-1} min.$^{-1}$)
	In C_6H_6.		*In* C_6H_6 *at* 25°.			*In* CCl_4.
10°	—	0·56 ± 0·08	H_2O (0·10)	40	10°	0·10 ± 0·02
25	—	1·5 ± 0·2	N^{IV} salt [b] (0·05)	55	25	0·40 ± 0·05 [c]
35		2·9 ± 0·4	EtOH (1·0)	80	35	1·2 ± 0·2
25	Glass capillaries [a]	1·4 ± 0·2	$COMe_2$ (1·0)	96		
25	$PhNO_2$ (3·0)	2·4 ± 0·3	Dioxan (0·30)	95		
25	Polymer (A) (0·024)	1·5 ± 0·2				

[a] These increased the surface : volume ratio by a factor of 6. [b] Tri-isobutylammonium trichloroacetate. [c] Mean from a set of tests similar to those shown in Fig. 3.

a summary of all the measurements being in Table 2. The percentage of retardation was calculated as described for Table 3 of a preceding paper.[10] Other experiments showed that vigorous drying, traces of peroxides, and molecular oxygen do not influence the rate in benzene at 25°. When the first and the last three k values of Table 2 are used the velocity coefficients in benzene and carbon tetrachloride can be represented, respectively, by:

$$k = 10^{4\cdot4 \pm 1\cdot0} \exp[(-11{,}000 \pm 1000)/\boldsymbol{RT}] \text{ (l. mole}^{-1} \text{ sec.}^{-1})$$

and

$$k = 10^{8\cdot6 \pm 1\cdot5} \exp[(-17{,}000 \pm 2000)/\boldsymbol{RT}] \quad ,, \quad ,,$$

In using expression (9) it was assumed that n remains constant throughout the reaction, the final values being in fact employed. This is justified by the results shown in Fig. 4 and by the observed agreement of velocity coefficients calculated with the help of expression (9), with an n value relating to 100% conversion and with the help of optical-density measurements.

Rate of Formation of Polymer (A) *if Cyclopentane is the Starting Material.*—The two simultaneous differential rate equations are:

$$dx/dt = k_1(c - 2x)(b - x + y - y/n)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$dy/dt = k(x - y)(b - x + y - y/n) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where c is the initial concentration of cyclopentadiene, k_1 is the velocity coefficient of reaction (1), its numerical value being one-half of the rate coefficient defined by equation 1 of a preceding paper,[10] x is the concentration of ester (I) at time t, and the other symbols have the same significance as in rate equation (6). If the trichloroacetic acid concentration, b, is much larger

* For individual k values in typical runs see ref. 6.

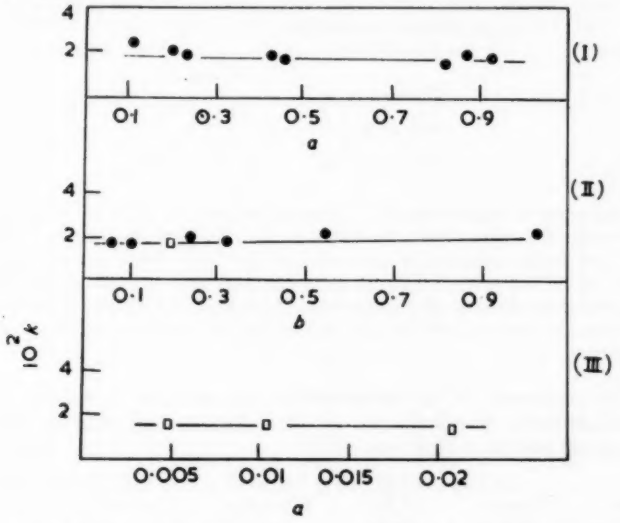
[11] Guggenheim, *Phil. Mag.*, 1926, **7**, 538.

XUM

than c, integration is possible, with the help of Laplace transform, but the velocity coefficients obtained in this way are not more accurate than those derived in a simple manner without integration. Differentiation of expression (11) and appropriate substitution lead to

$$k' = \frac{\ddot{y}/c + 2k_1'\dot{y}/c}{2k_1'(\frac{1}{2} - y/c) - \dot{y}/c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

FIG. 3. *Rate of trichloroacetic acid-catalysed conversion of ester* (I) *into polymer* (A); *benzene at* 25°. *a, b: Initial concns. of ester* (I) *and trichloroacetic acid* (mole l.$^{-1}$) *respectively. Velocity coefficients, k, in* l. mole^{-1} min.$^{-1}$.



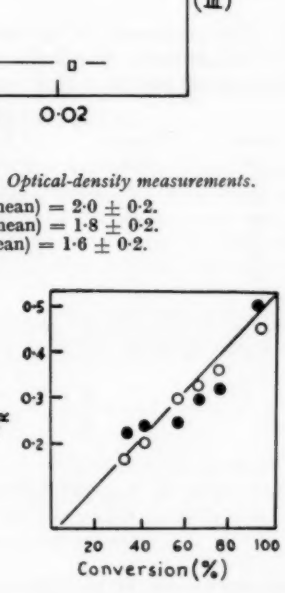
● *Titration of released trichloroacetic acid.* □ *Optical-density measurements.*

(I): $b = 0{\cdot}123 - 0{\cdot}403$; 10^2k (mean) $= 2{\cdot}0 \pm 0{\cdot}2$.
(II): $a = 0{\cdot}339 - 0{\cdot}448$; 10^2k (mean) $= 1{\cdot}8 \pm 0{\cdot}2$.
(III): $b = 0{\cdot}251 - 2{\cdot}09$; 10^2k (mean) $= 1{\cdot}6 \pm 0{\cdot}2$.

FIG. 4. *Trichloroacetic acid-catalysed conversion of ester* (I) *into polymer* (A); *benzene solution at* 25°. N_R' = *number of* C_{10} *residues per l. of solution incorporated into polymer. Initial concn.: ester* (I) 0·498M; *trichloroacetic acid* 0·500M.

○, *Calc. from expression* (9) *with the assumption that* $n = 7$, *throughout the run.*

●, *Calc. from results of electrical conductance measurements, with graphs similar to those shown in Fig.* 1.



where $k_1' = k_1b^2$ and $k' = kb$. The first and second derivatives, $\dot{y}/c$ and $\ddot{y}/c$, in (12) can be computed from a set of finite differences [12] (see Table 3), provided the experimental determination of y/c is carried out at equal intervals (ω) of time. For computation of the first derivative,

[12] Milne, "Numerical Calculus," Princeton Univ. Press, 1949, Chapter VI; see also "Interpolation and Allied Tables," H.M. Stationery Office, London, 1936.

XUM

$\dot{y}/c$, a set of finite differences, $\Delta_0' = \frac{1}{2}(\delta'_{-\frac{1}{2}} + \delta'_{+\frac{1}{2}})$, $\Delta_1' = \frac{1}{2}(\delta'_{\frac{1}{2}} + \delta'_{\frac{3}{2}})$, etc., and $\Delta_0''' = \frac{1}{2}(\delta'''_{-\frac{1}{2}} + \delta'''_{+\frac{1}{2}})$, etc., is required. The first and second derivatives, for instance at time t_0, are given by: [12]

$$\left.\begin{aligned}\omega(\dot{y}/c)_{t=0} &= \Delta'_0 - \tfrac{1}{6}\Delta'''_0 + \tfrac{1}{30}\Delta_0^{V} \ldots\ldots \\ \omega^2(\ddot{y}/c)_{t=0} &= \delta''_0 - \tfrac{1}{12}\delta_0^{IV} + \tfrac{1}{90}\delta_0^{VI} \ldots\ldots\end{aligned}\right\} \quad (13)$$

and similarly for other t values.

TABLE 3. *Finite differences of the type used for computation of the first and second derivatives in rate equation* (12).

Time	Experimentally determined function of time	Finite differences			
		$\delta'_{-3/2}$			
t_{-1}	$(y/c)_{t=-1}$		δ''_{-1}		$\delta^{IV}{}_{-1}$
		$\delta'_{-1/2}$		$\delta'''_{-1/2}$	
t_0	$(y/c)_{t=0}$		δ''_0		δ_0^{IV}
		$\delta'_{+1/2}$		δ'''_{+1}	
t_1	$(y/c)_{t=+1}$		δ''_{+1}		$\delta^{IV}{}_{+1}$

$(y/c)_t$ was determined experimentally by measuring in the absence of molecular oxygen, the optical densities including those corresponding to 100% polymerisation. For the present purpose it is sufficiently accurate to use only the first two terms on the right-hand side of expression (13), etc. The rate coefficients determined in this way are in the fifth column of Table 4. The values in the last column relate to experiments in which the isolated ester (I) was the starting material; the two sets of rate coefficients agree within the limits of the combined experimental errors.

TABLE 4. *Rate coefficients, k, of trichloroacetic acid-catalysed formation of polymer* (A). [*The k values relate to experiments in which the starting materials were respectively cyclopentadiene and the isolated ester* (I).]

		Initial concn. (mole l.$^{-1}$)		10^2k (l. mole^{-1} min.$^{-1}$)	
Temp.	Solvent	C_5H_6	$CCl_3{\cdot}CO_2H$	from (12)	from (7)
20°	CCl_4	0·0421	2·22	0·21 ± 0·03	0·28 ± 0·03
20	,,	0·0413	1·12	0·20 ± 0·03	
20	,,	0·00706	1·14	0·26 ± 0·04	
20	C_6H_6	0·0220	2·09	1·0 ± 0·2	1·3 ± 0·2
20	,,	0·0234	1·61	1·0 ± 0·3	
31	,,	0·0240	0·544	1·4 ± 0·4	2·2 ± 0·4
40	,,	0·0229	0·500	3·0 ± 0·6	4·0 ± 0·6

If b and x in expressions (10) and (11) are of the same order of magnitude, one rearranges and differentiates equation (11), thus obtaining:

$$x = \frac{b}{2} + \frac{(2n-1)}{2n}y - \sqrt{\left[\left(\frac{b}{2} - \frac{y}{2n}\right)^2 - \frac{1}{k}\dot{y}\right]} \quad (14)$$

$$\dot{x} = \frac{(2n-1)}{2n}\dot{y} + \tfrac{1}{2}\left\{\frac{\left(\frac{b}{2} - \frac{y}{2n}\right)\frac{\dot{y}}{n} + \frac{1}{k}\ddot{y}}{\sqrt{\left[\left(\frac{b}{2} - \frac{y}{2n}\right)^2 - \frac{1}{k}\dot{y}\right]}}\right\} \quad (15)$$

Introducing expressions (14) and (15) into (10) and determining y, $\dot{y}$, and $\ddot{y}$, as described above, leads to a biquadratic equation,[13] which can be solved for k. Some of the coefficients, however, are small differences of large quantities the accuracy of which is only 10—15% so that sufficiently accurate values of k cannot thus be obtained. If, on the other hand, a velocity coefficient, k from Table 2 or 4 is introduced into expression (14), the value of x can be computed. Typical results are in Fig. 5, which also shows experimentally determined y values. In the early stages

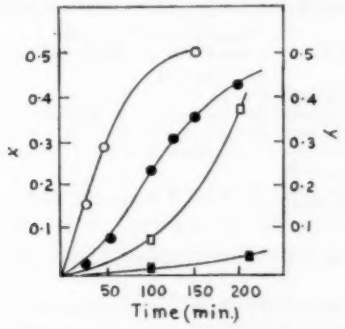
[13] See Appendix 4 of ref. 6.

XUM

of these reactions, y is relatively small, which is to be expected, of course, in view of the preparative isolation [2] of ester (I).

Oxidation of Ester (I) *and of the Alcohol derived from It.*—Ozone was bubbled at −20°, for 13 hr., through a solution of ester (I) (25 g.) in ethyl acetate (100 ml.). After the solution had been left for 5 days at +20°, 30% hydrogen peroxide (25 ml.) in acetic acid (50 ml.) was added, and the whole was left at +20° for 12 hr. and refluxed for 30 min. The solvent and hydrogen peroxide were distilled off and the residue, a viscous paste, was dried. Sublimation at 160°/0·1 mm. gave succinic acid, m. p. and mixed m. p. 182° (from acetone), whose identity was confirmed by conversion into the *p*-bromophenacyl ester.

FIG. 5. *Trichloroacetic acid-catalysed conversion of cyclopentadiene into ester* (I) *and polymer* (A) *at* 25°; x *and* y (mole $l.^{-1}$) *are defined by rate equations* (10) *and* (11).



Solvent	Initial concn. (M) C_5H_6	$CCl_3{\cdot}CO_2H$	Symbol
C_6H_6	0·972	1·00	○ ●
CCl_4	1·00	0·996	□ ■

○ and □ relate to left ordinate: ● and ■ relate to right ordinate.

3-(Cyclopenta-2,4-dienyl)cyclopentanol [2] (4 g.) in benzene (500 ml.) and an aqueous solution (1100 ml.) of potassium permanganate (25 g.) and sodium carbonate (40 g.) were shaken for 2 days at 20° and then refluxed for 2 hr. After separation of the benzene layer, the pH of the alkaline solution was brought to 2·3 by addition of concentrated phosphoric acid, a precipitate being dissolved with 30% hydrogen peroxide. The resulting solution was extracted with boiling ether for 5 days; after drying and removal of ether, the residue was sublimed *in vacuo* and recrystallised from acetone, giving succinic acid, m. p. 182°, identified as above.

The mechanism of these oxidations is not known, but it can be concluded that the formation of succinic acid is preceded by a shift of hydrogen from positions 1′,3 to 2′,3′ (cf. ref. 14). This rearrangement is similar to one postulated below.

DISCUSSION

Kinetics.—Conversion of ester (I) under catalysis by trichloroacetic acid into polymer (A) is kinetically similar to certain addition polymerisations [15] in which the growing polymer reacts with monomer, thereby forming products of relatively low molecular weight. The following reactions account for the observed kinetics:

Initiation: $$C_{10}H_{13}B + HB \underset{k'}{\overset{k_1}{\rightleftharpoons}} (RB)^+ \cdots B^- \quad (16)$$

Propagation: $$(R_rB)^+ \cdots B^- + C_{10}H_{13}B \xrightarrow{k_p} (R_{r+1}B)^+ \cdots B^- + HB \quad (17)$$

Termination: $$(R_rB)^+ \cdots B^- + C_{10}H_{13}B \xrightarrow{k_{10}} (R_{r+1}B) + 2HB \quad (18)$$

[14] Formula (II) of ref. 2.
[15] Laible, *Chem. Rev.*, 1958, **58**, 807.

XUM

where $C_{10}H_{13}B$, HB, and R represent the ester (I), trichloroacetic acid, and C_{10} residues incorporated into the growing carbonium ions, R_rB^+, and into the dead polymer homologues, R_rB, of degree of polymerisation r; k_i, k'_i, k_p, and k_{te} are velocity coefficients. The termination (18) describes a situation in which the acid concentration is so low that the equilibrium [1] between dead polymer and acid is far on the side of the deprotonated species. If the acid concentration is high, *e.g.* M, the dead polymer is almost completely protonated.[1] The resulting dead carbonium-ion pairs [1] are assumed to be different from the growing carbonium-ion pairs formed in reactions (16) and (17), for reasons outlined on p. 1973. Both in the growing and in the dead carbonium-ion pairs the trichloroacetate counterion,

TABLE 5. *Numerical values of rate coefficients, k_i, ratios k_{te}/k_p and of the relevant non-exponential A factors and activation energies, E.*

Temp.	$10^3 k_i$ (l. mole^{-1} min.$^{-1}$)	k_{te}/k_p	$\log_{10} A_i$ (A_i in l. mole^{-1} sec.$^{-1}$)	E_i (kcal. mole^{-1})	$\log_{10}(A_{te}/A_p)$	$-(E_{te} + E_p)$ (kcal. mole^{-1})
			In C_6H_6.			
10°	0·93 ± 0·09	0·25 ± 0·03	1·6 ± 1	8·3 ± 1	−4 ± 2	4·5 ± 1·5
25	2·1 ± 0·2	0·20 ± 0·02				
35	2·9 ± 0·3	0·13 ± 0·02				
			In CCl_4.			
10	0·17 ± 0·02	0·25 ± 0·03	4·7 ± 1	13·3 ± 1		
25	0·57 ± 0·06	0·20 ± 0·02				
35	1·2 ± 0·1	0·13 ± 0·02				

B^-, must be firmly bound to the cation, because of the low dielectric constant of the solvent.

By assuming that the stationary-state approximation is valid, that $k_{te}/k_p = \lambda$ is independent * of r, and that $(k_p + k_{te})[C_{10}H_{13}B] \gg k'_i$, it can be shown that

$$-d[C_{10}H_{13}B]/dt = k_i\{(2\lambda + 1)/\lambda\}[C_{10}H_{13}B][HB] \quad . \quad . \quad . \quad . \quad (19)$$

$$n = (2\lambda + 1)/\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$f_m = \lambda(1 + \lambda)^2/(1 + \lambda)^{r+1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$f_w = \{(132{\cdot}1r + 163{\cdot}4)/(1 + \lambda)^{r+1}\}\left\{132{\cdot}1\left[\frac{1}{\lambda^2} - \frac{1}{(1 + \lambda)^2}\right] - \frac{163{\cdot}4}{(1 + \lambda)^2\lambda}\right\} \quad (22)\ \dagger$$

where $-d[C_{10}H_{13}B]/dt$ and n are the rate and the number-average degree of polymerisation, f_m is the mole fraction and f_w is the weight fraction of an r-mer. According to expressions (19) and (20) the rate of polymerisation is proportional to the first power of the ester and acid concentration and n is independent of the initial concentrations and of the degree of conversion. All this is in agreement with the experimental results. The retardation by added proton-acceptors is qualitatively similar to effects observed in other reactions [9,10] involving proton-transfer.

If one attempted to explain only the kinetics of this polymerisation one could postulate an initiation $C_{10}H_{13}B + HB \longrightarrow C_{10}H_{13}^+ \cdots (BHB)^-$ and identity of k_i with the velocity coefficient, designated in a previous paper [10] by k_5'. These suppositions,‡ however, do not account for the structural aspects to be discussed below. The principle of microscopic reversibility requires that on addition of trichloroacetic acid to ester (I) the intermediate [10] i'' is formed. It is possible, however, that $k_i > k_5'$, and in this case the formation of i'' would be kinetically without consequence.

* The following formula can, however, also be derived if it is assumed that λ depends on r in the manner specified by Murphy and Wassermann.[16]

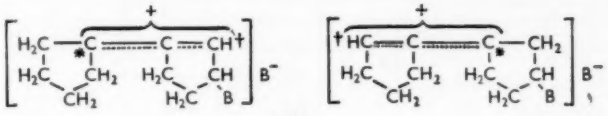
† Details of calculation are given in ref. 6, p. 82.

‡ It is recognised that such triple ions as $(BHB)^-$ are of importance for other reactions.[17]

[16] Murphy and Wassermann, *J. Polymer Sci.*, 1954, **14**, 477.

[17] Cf. Pocker, *J.*, 1958, 4327.

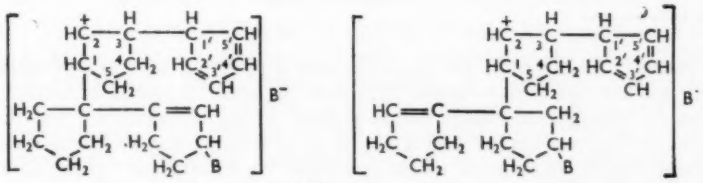
The numerical values of rate coefficient k_i and ratios k_{te}/k_p are in the second and third column of Table 5; they were calculated from the figures in the first three lines of columns 3 and 7 of Table 2, expressions (19) and (20) being taken into account. The relevant A and E values of the Arrhenius rate equation are also given in Table 5. The ratio k_{te}/k_p (third column) decreases with increasing temperature, so that the activation energy of propagation, E_p, must be larger than the activation energy of termination, E_{te}; k_p is nevertheless larger than k_{te}, the influence of the activation energies being overcompensated by that of the A factors, as shown by the figures in the last two columns.



(A)

Isomeric ion pairs formed in the initiating reaction (16), *designated by* $(RB)^+ \cdots B^-$, R *being a* C_{10} *residue. These species are formed if "end-on" protonation of the two conjugated carbon–carbon double bonds in ester* (I) *occurs. The isomer on the right is formed if hydrogen-shift occurs from positions* 3,1′ *to* 3′,4′; *the* 5′*-hydrogen atom is derived from the proton donor.*

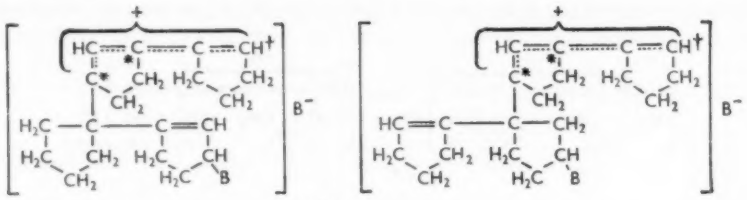
The Build-up Principle.—It is assumed that proton-transfer to ester (I) in the initiation reaction (16) is followed by a shift of hydrogen, thereby producing carbonium ions shown in (A). Oxygen of the trichloroacetate grouping in ester (I) may also be protonated, but this is not shown as it is not essential for this reaction. In the propagation steps (17), the elimination of trichloroacetic acid, HB, from ester (I), $C_{10}H_{13}B$, is regarded as a reverse acid addition to an olefin, $C_{10}H_{12}$, which participates in the formation of the growing carbonium ions, as shown in (B) and (C). This mode of reaction is assumed to be typical for all propagation steps. All growing carbonium ions are mesomers, so that each propagation step must lead to structural isomers, unless this interferes with stereochemical requirements; the number of structural isomers increases with increasing degree of polymerisation. In (A) and (C) some carbon atoms are indicated by asterisks or daggers, and these are, respectively the potential junction points of C_{10} residues for propagation



(B)

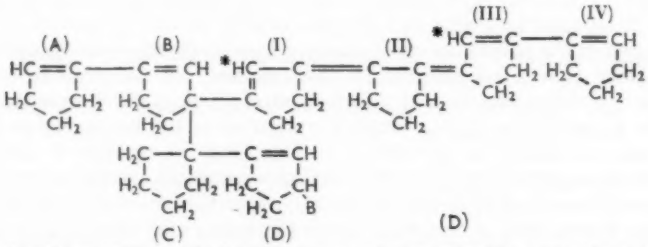
or termination. Carbon atoms indicated by an asterisk are joined to three others; those indicated by daggers are linked to two carbon and one hydrogen atom. In the termination step (18), elimination of trichloroacetic acid HB from ester (I), incorporation of the species $C_{10}H_{12}$, and rearrangement are assumed to occur, as they do in the propagation steps (17). The difference between the two steps (17) and (18) lies in the fact that species (C) and similar growing carbonium-ion pairs cannot be deprotonated with formation of a double bond between C_{10} residues. In the carbonium ions formed in reaction (18), on the other hand, deprotonation with double-bond formation is possible, because the junction points between C_{10} residues are carbon atoms of a different type, as indicated above and in the legends below (A). The structure of the carbonium ions formed in reaction (18) is such that deprotonation leads, not only to a new double bond, but also to a sequence of five conjugated double bonds if $r \geqslant 3$ and to a sequence of four conjugated double bonds if

$r = 2$. A typical deprotonated dead polymer homologue is shown in (D).* Proton-transfer to the five conjugated double bonds leads to the corresponding dead carbonium-ion pair, the mesomeric part of which is shown in Fig. 8b of the preceding paper.[1] Carbonium-ion pairs of this kind contain four formal conjugated double bonds, while the mesomeric part of the growing carbonium-ion pair (see C) contains only two formal conjugated double bonds. For this reason it is suggested that the dead carbonium-ion pairs



(C)

Growing carbonium ion pair, formed from the intermediate (B) *by a shift of hydrogen from positions* 1,3, 1 *to* 2′,3′,4′. *These species are designated by* $(R,B)^+ \cdots B^-$, *the degree of polymerisation,* r, *being* 2 *in this case.*



(D)

Dead polymer homologue of degree of polymerisation, $r = 4$. *In attempting to build up this species with space-filling models, there is no difficulty in joining together rings* A, B, C, D, *and* IV, *but some strain occurs in joining rings* I, II, *and* III. *Owing to the exocyclic double bonds two hydrogen atoms indicated* * *are forced close together; in order to accommodate them a coplanar orientation of rings* I, II, *and* III *has to be avoided.*

are more stable. The polymer (D) contains also a sequence of two conjugated double bonds and one isolated double bond. Polymers in which $r > 4$ still contain only one sequence of five conjugated double bonds (formed in the termination), but the number of sequences of two conjugated double bonds or of isolated double bonds increases. If $r > 2$, straight-chain polymers in which successive C_{10} residues are arranged in a linear fashion cannot be formed, non-linear species such as (D) being obtained.

This build-up principle accounts for the observed [1] total number of double bonds; for the presence [1] of one trichloroacetate grouping,† B, in one mole of the polymer; for the non-linear structure;[1] for the presence of a long and a short sequence of conjugated double bonds, as indicated by the electronic spectrum [1] of the polymer; and for the kinetics of polymerisation.

The proton-transfer to ester (I) in reaction (16) or the elimination of trichloroacetic acid in reactions (17) and (18) may be synchronised with the shift of hydrogen indicated in the legend below (A) and (C) or with the formation of the bonds joining the C_{10} residues, R, together, and with the subsequent rearrangements (see B and C). It is also possible, however, that reactions (16), (17), and (18) are each a set of consecutive processes, this not

* The structure of similar species is shown in Figs. 20—22 of ref. 6.

† According to the suggested mechanism, the presence of the trichloroacetate grouping is due to the mode of initiation, not to the collapse of a growing carbonium-ion pair.

being incompatible with the assumption that the " over-all " initiation, propagation, and termination are each kinetically of the second order. The rearrangements, specified above, may be due to hydride-transfers, which have been invoked before to explain isomerisation occurring in cationic polymerisation [18] and carbonium ions occurring in other reactions.[19] This mechanism is more satisfactory than one involving a rapidly established pre-equilibrium between ester (I) and an isomer. It is admitted, however, that a pre-equilibrium could also be reconciled with the observed kinetics.

Unsatisfactory Alternative Structure of Polymer (A).—A different build-up principle could operate if all the double bonds in this polymer were conjugated. One could argue that this is actually the case and that the observed electronic spectrum of the polymer is to be regarded as superposition of the spectra of each polymer homologue. In order

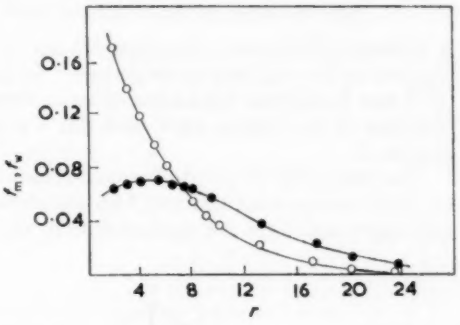


FIG. 6. *Molecular-weight distribution of polymer* (A) *in benzene at* 25°, *calculated from equations* (21) *and* (22).

○ *Mole fractions,* f_m.
● *Weight fractions,* f_w (*not referred to in text*).

to find out whether this hypothesis is justified the over-all light absorption coefficients, ε, of the polymer were calculated with the help of appropriate mole fractions, $f_m(r)$, taken from Fig. 6 and with ε_r values taken from open-chain reference polyenes containing a known number of conjugated double bonds. The ε values were represented by

$$\varepsilon = \sum_{r=2}^{r=15} \varepsilon_r f_m(r) + \sum_{r=16}^{r=\infty} \varepsilon_r f_m(r) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where the ε_r values in the first term on the right-hand side relate to reference polyenes [20] containing 2—15 conjugated double bonds, it being assumed that the values of the reference polyene and of the r-mers are identical if the number of conjugated double bonds is the same. Fig. 6 shows that the mole fractions $f_m(r)$ become small if $r > 15$, and it is justified, as a first approximation, to calculate the last term of expression (23) on the assumption that the relevant light-absorption coefficients are the same as those of another open-chain reference polyene [22] with 19 conjugated double bonds (open-chain polyenes with more than 19 conjugated double bonds are not known). The superposition spectrum of polymer (A) calculated in this manner [23] shows peaks at 320, 440, and 480 mμ, with ε values of about 3×10^4. In the observed electronic spectrum,[1] on the other hand, there are no peaks at wavelength longer than 360 mμ.

We are grateful to the Czech Refugee Trust Fund for a grant (to L. R.).

WILLIAM RAMSAY AND RALPH FORSTER LABORATORIES,
UNIVERSITY COLLEGE,
GOWER STREET, LONDON, W.C.1. [*Received, May* 18*th*, 1960.]

[18] Fontana, " Cationic Polymerisation " (ed. Plesch), Heffer, Cambridge, 1953, p. 121.
[19] See, *e.g.*, Deno, Peterson, and Saines, *Chem. Rev.*, 1960, **60**, 7.
[20] Ref. 21 of the preceding paper.
[22] Karrer and Eugster, *Helv. Chim. Acta*, 1951, **34**, 1805.
[23] Cf. ref. 6, Appendix 8.

XUM

378. *The Crystal and Molecular Structure of* (+)-10-*Bromo*-2-*chloro*-2-*nitrosocamphane.*

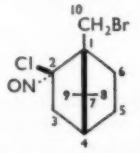
By G. Ferguson, C. J. Fritchie, J. Monteath Robertson, and G. A. Sim.

Crystals of (+)-10-bromo-2-chloro-2-nitrosocamphane have been subjected to quantitative *X*-ray analysis. They are orthorhombic, of space group $P2_12_12_1$-D_2^4, with eight molecules of $C_{10}H_{15}BrClNO$ in the unit cell. The asymmetric crystal unit consists of two chemical molecules. Successive three-dimensional Fourier syntheses served to locate all the atoms apart from hydrogen. The two crystallographically independent molecules appear to be identical chemically, differing only in orientation in the unit cell. The presence of the bulky chlorine atom *cis* to the CMe_2 bridge causes some distortion of the camphane molecular framework.

A number of rotatory dispersion studies of monomeric nitroso-compounds have been reported by Mitchell and his co-workers. In the case of (−)-2-chloro-2-nitrosocamphane[1,2] (I) it was found that irradiation of an alcoholic solution with red light caused a gradual inversion of the Cotton effect and this was attributed to inversion of configuration at position 2.

The behaviour of (+)-10-bromo-2-chloro-2-nitrosocamphane (II) on irradiation with red light is somewhat different,[3] for although the Cotton effect is altered its sign remains unchanged and there is a marked shift in the absorption maximum, suggesting that the

(I)



(II)

change in molecular structure on irradiation in this case may not be simply an inversion at position 2. An *X*-ray study of the starting material and of the irradiated material seemed an attractive way of establishing the details of the reaction in this case, and we have now completed the analysis of the starting material and find that its stereochemistry is represented by (II) (or its mirror image). It is hoped to be able to report the study of the irradiated material later.

Crystal Data.—(+)-10-Bromo-2-chloro-2-nitrosocamphane, $C_{10}H_{15}BrClNO$; $M = 280{\cdot}6$. Orthorhombic, $a = 23{\cdot}11$, $b = 11{\cdot}32$, $c = 9{\cdot}03$ Å, $U = 2362$ Å^3, $D_m = 1{\cdot}562$ (by flotation), $Z = 8$, $D_c = 1{\cdot}578$, $F(000) = 1136$, space group $P2_12_12_1$ (D_2^4). Absorption coefficient for *X*-rays ($\lambda = 1{\cdot}542$ Å), $\mu = 66{\cdot}7$ cm.$^{-1}$.

Structure Analysis.—The crystal data show that the asymmetric crystal unit consists of two crystallographically independent chemical molecules, necessitating the location of 28 atoms other than hydrogen. Because of the presence of the bromine and chlorine atoms, however, there was no need to postulate trial structures with assumptions as to the stereochemistry and relative orientation of the molecules, the analysis proceeding on the basis of the usual phase-determining heavy-atom method.

The positions of the bromine atoms were determined initially from two-dimensional Patterson syntheses along the *b* and *c* crystal axes and were confirmed by inspection of the three-dimensional Patterson function. The projections are shown in Fig. 1.

Attempts to elucidate the structure in projection proved fruitless because of the considerable overlap and in consequence recourse was made to three-dimensional methods for the location of the remaining atoms in the asymmetric crystal unit. The first three-dimensional Fourier synthesis was calculated with phase angles appropriate to the bromine atoms alone and served

[1] Mitchell, Watson, and Dunlop, *J.*, 1950, 3440.
[2] Hope and Mitchell, *J.*, 1953, 3483.
[3] Davidson, Ph.D. Thesis, University of Glasgow, 1958.

XUM

to locate the two chlorine atoms in the asymmetric unit. A number of other peaks corresponding to some of the lighter atoms were also well resolved in this synthesis, but as it was not possible at this stage to identify chemically many of these atoms with certainty, only the bromine and chlorine atoms were included in the next calculation of phase angles.

The improved phase angles were employed in the computation of a second three-dimensional Fourier synthesis in which it was possible to locate, in addition to the bromine and chlorine atoms, the nitroso-group and carbon atoms (1), (2), (3), (4), and (10) of both molecules in the asymmetric crystal unit. These atoms were then included in the calculation of a third set of phase angles which led, in turn, to a third three-dimensional Fourier synthesis in which all the atoms (apart from hydrogen) in the asymmetric crystal unit could be located.

FIG. 1*a*.

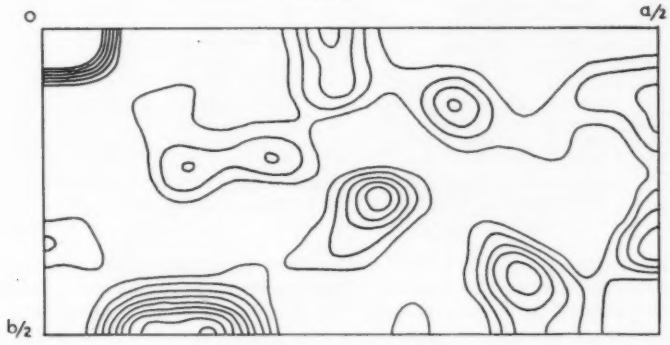


FIG. 1*b*.

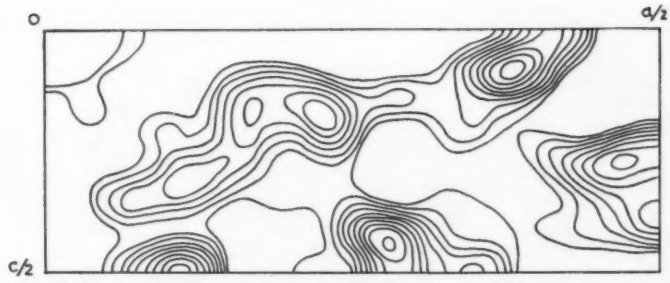


FIG. 1*a and b*. *Patterson projections along the c and b axes. Contour scale arbitrary.*

Refinement was continued by means of a further F_o synthesis, followed by a cycle of least-squares adjustment of the positional and thermal parameters of the bromine, chlorine, nitrogen, and oxygen atoms, and completed by calculation of a final F_o synthesis with correction for termination-of-series errors by means of an F_c synthesis. The final average discrepancy between observed and calculated structure amplitudes is 15·5%.

The final co-ordinates are listed in Table 1, details of the progress of the structure analysis are shown in Table 2, and the final set of calculated and observed structure amplitudes is given in Table 3.

Superimposed contour sections parallel to (001) illustrating the final electron-density distribution over the two molecules in the asymmetric crystal unit are shown in Fig. 2. The atomic arrangement corresponding to this electron-density distribution is illustrated in Fig. 3.

Discussion.—In the application of the heavy-atom method to a non-centrosymmetrical crystal structure such as the present, the final electron-density distribution is dependent to a considerable extent on the choice of the correct set of atomic sites for the lighter atoms. It is not too difficult to obtain reasonable electron-density distributions in which wrongly placed

XUM

or even completely spurious atoms are present. This is brought out clearly, for example, in the description by Hodgkin *et al.* of the analysis of the structure of B_{12} hexacarboxylic acid.[4] In the case of projections along the crystallographic axes in $P2_12_12_1$, however, centrosymmetrical electron-density distributions are involved and these are much less dependent on the assumed light-atom positions, the signs of the structure factors employed in the Fourier syntheses being largely determined by the heavy atoms, *i.e.*, by the bromine and chlorine atoms in the present

FIG. 2. *Final three-dimensional electron-density distribution for* (+)-10-*bromo*-2-*chloro*-2-*nitrosocamphane, shown by means of superimposed contour sections parallel to* (001). *Contour interval* 1e/Å^3 *except around the* Cl *and* Br *atoms where it is* 2e/Å^3 *and* 5e/Å^3, *respectively.*

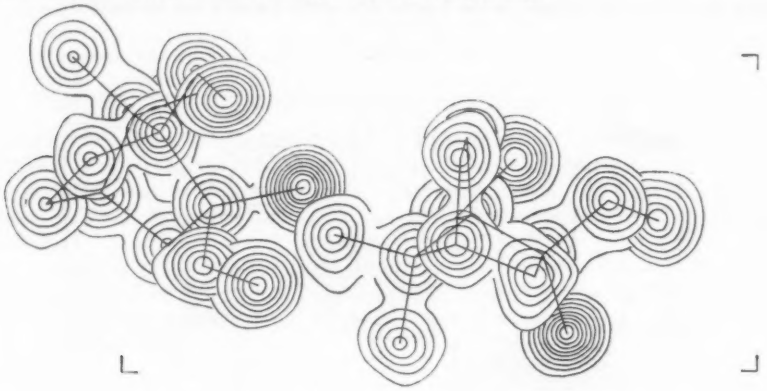
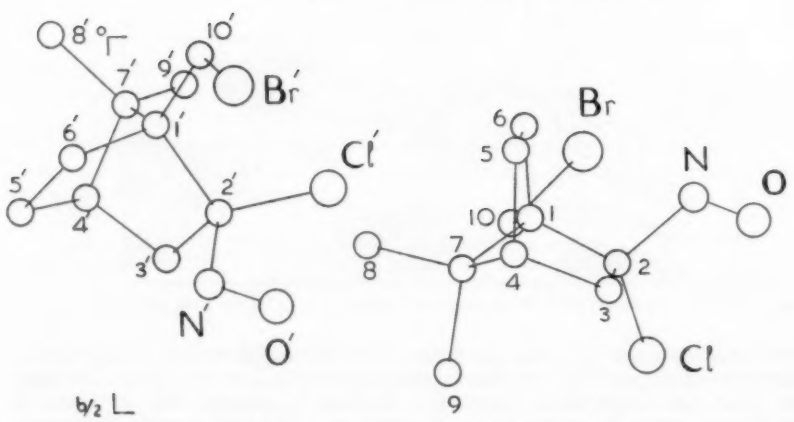


FIG. 3. *Atomic arrangement corresponding to* Fig. 2.



case. It is gratifying that the atomic positions deduced by the three-dimensional Fourier method conform extremely well with the electron-density projection along the *c* axis shown in Fig. 4.

The interatomic distances and interbond angles calculated from the atomic co-ordinates listed in Table 1 are given in Table 4. The two crystallographically independent molecules in the asymmetric crystal unit appear to be identical chemically. Even the bromine and oxygen atoms, which because of easy rotation about the C–C and C–N single bonds might have been expected to have rather different orientations in the two molecules, appear in fact to occupy positions with respect to the carbon framework of each molecule which are very similar.

[4] Hodgkin, Pickworth, Robertson, Prosen, Sparks, and Trueblood, *Proc. Roy. Soc.*, 1959, *A*, **251**, 306.

This is brought out clearly by examining the distances (Table 4) between bromine and oxygen atoms and carbon atoms. In each case $d(\mathrm{Br}\cdots\mathrm{C}(n)) \approx d(\mathrm{Br}'\cdots\mathrm{C}(n'))$ and $d(\mathrm{O}\cdots\mathrm{C}(n)) \approx d(\mathrm{O}'\cdots\mathrm{C}(n'))$. In view of this identity of the two molecules averaged dimensions for the molecule of (+)-10-bromo-2-chloro-2-nitrosocamphane are also listed in Table 4.

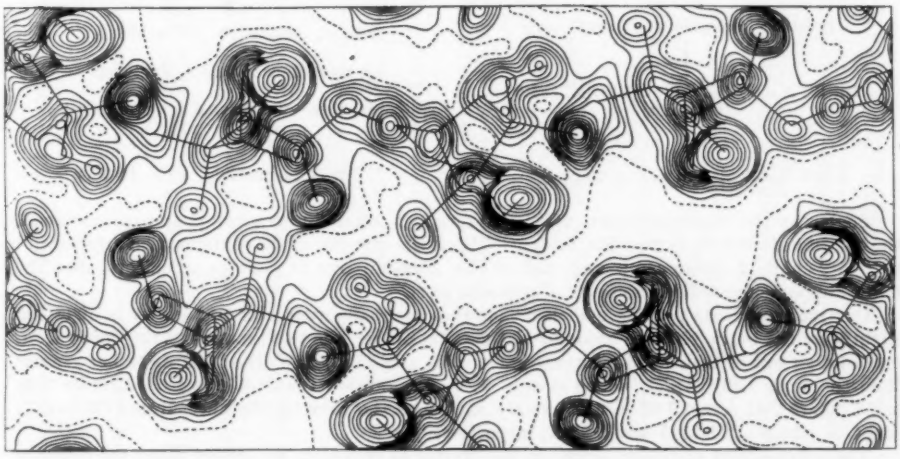
TABLE 1. *Co-ordinates of the atoms in the asymmetric crystal unit. (Origin of co-ordinates as in International Tables.)*

Atom	*x/a*	*y/b*	*z/c*	*B* *	Atom	*x/a*	*y/b*	*z/c*	*B* *
C(1)	0·2741	0·2545	0·0246	5·4	C(1′)	0·0317	0·1241	0·4058	5·4
C(2)	0·3311	0·3163	−0·0216	5·4	C(2′)	0·0703	0·2348	0·4350	5·4
C(3)	0·3232	0·3574	−0·1848	5·4	C(3′)	0·0373	0·2962	0·5685	5·4
C(4)	0·2643	0·2998	−0·2209	5·4	C(4′)	−0·0154	0·2191	0·5938	5·4
C(5)	0·2662	0·1599	−0·2217	5·4	C(5′)	−0·0607	0·2319	0·4679	5·4
C(6)	0·2723	0·1296	−0·0549	5·4	C(6′)	−0·0272	0·1662	0·3450	5·4
C(7)	0·2296	0·3198	−0·0800	5·4	C(7′)	0·0102	0·0897	0·5691	5·4
C(8)	0·1653	0·2850	−0·0766	5·4	C(8′)	−0·0366	−0·0026	0·5710	5·4
C(9)	0·2182	0·4556	−0·0368	5·4	C(9′)	0·0591	0·0582	0·6787	5·4
C(10)	0·2616	0·2578	0·1905	5·4	C(10′) ...	0·0607	0·0243	0·3240	5·4
O	0·4239	0·2620	0·0355	7·1	O′	0·1060	0·3646	0·2634	6·8
N	0·3807	0·2288	−0·0153	5·7	N′	0·0638	0·3307	0·3314	7·1
Br	0·3095	0·1662	0·3075	6·2	Br′	0·0817	0·0664	0·1290	6·5
Cl	0·3503	0·4429	0·0899	6·0	Cl′	0·1437	0·2090	0·4727	6·0

* The values of *B* for the C atoms are the isotropic values used in the analysis. The values of *B* for the O, N, Br, and Cl atoms are average values derived from the anisotropic parameters of the least-squares analysis.

The estimated standard deviation in bond length calculated from the differences between the two molecules is 0·044 Å. The corresponding value deduced from the least-squares calculation at an earlier stage is 0·080 Å. For the averaged dimensions in Table 4 we may take $0{\cdot}064/\sqrt{2}$, *i.e.*, 0·045 Å, as a reasonable estimate of the standard deviation in bond length.

FIG. 4. *Electron-density projection on* (001). *Contour interval* 1e/Å², *the* 1e/Å² *line being broken, except around the* Cl *atoms above* 6e/Å² *where the interval becomes* 2e/Å², *and around the* Br *atoms above* 5e/Å² *where the interval becomes* 5e/Å². *The positions deduced for the atoms by the three-dimensional refinement procedure are indicated.*



The average carbon–carbon single bond length is 1·554 Å, not significantly different from the value of 1·545 Å in diamond.

For the nitroso-grouping the C–N separation of 1·48 Å is in agreement with the accepted value of 1·48 Å for a C–N single bond. The N–O separation of 1·19 Å is slightly shorter than

the value of about 1·21 Å appropriate to a nitro-group, but in view of the fairly large standard deviation too much significance should not be attributed to the difference. The separation is very significantly shorter than the value of 1·36 Å appropriate to a single bond, suggesting that the N–O bond has a large amount of double-bond character and may in fact be a pure double bond. The angle CNO is 118°.

Two *X*-ray studies of dimeric nitroso-compounds have been reported,[5] but only one previous structure analysis of a monomeric organic nitroso-compound has been described.[6] *p*-Iodonitrosobenzene is a planar molecule with d(C–N) = 1·28, d(N–O) = 1·24 Å, ∠(C–N–O) = 125°. The short C–N bond may be indicative of conjugation across the benzene ring, but as relatively few intensity data were obtained and the analysis was confined to projections the light-atom positions may be subject to considerable error.

Various metallic nitrosyls have been described,[7] but the electronic structures of these must be different, for the metal–nitroso-grouping is invariably approximately linear. In the nitrosyl halides,[8] however, the angle at the nitrogen atom is 116° in good agreement with our value of 118°, though the N–O separation of 1·14 Å is somewhat shorter than our value of 1·19 Å.

TABLE 2. *Progress of the structure analysis.*

Patterson syntheses
↓
Br (2 atoms)
↓
1st F_o calculation
1st three-dimensional F_o synthesis
↓
Br, Cl (4 atoms)
↓
2nd F_c calculation (R = 36·4%)
2nd three-dimensional F_o synthesis
↓
Br, Cl, N, O, C(1), C(2), C(3), C(4), C(10) (18 atoms)
↓
3rd F_c calculation (R = 29·6%)

3rd three-dimensional F_o synthesis
↓
Br, Cl, N, O, C(1) · · · C(10) (28 atoms)
↓
4th F_c calculation (R = 24·6%)
4th three-dimensional F_o synthesis
↓
5th F_c calculation (R = 21·8%)
Least-squares refinement
↓
6th F_c calculation (R = 16·4%)
5th three-dimensional F_o synthesis
1st three-dimensional F_c synthesis
↓
7th F_c calculation (R = 15·5%)

So far as the stereochemistry of (+)-10-bromo-2-chloro-2-nitrosocamphane is concerned, the chlorine atom is *cis* to the CMe_2 bridge. This is the opposite of the configuration attributed [2] to (−)-2-chloro-2-nitrosocamphane, and in this connection it is perhaps significant that the two compounds have Cotton effects of opposite sign.

Our measurements provide evidence that the camphane molecular framework is distorted slightly by the bulky chlorine atom *cis* to the CMe_2 bridge, the two groups bending away from one another out of their ideal positions. Thus the angle C(2)C(1)C(7) at 102° is rather greater than the angle C(6)C(1)C(7) which is only 97°. In addition the distances from C(2) to C(7) and C(9) are 2·44 Å and 3·02 Å, respectively, rather greater than the distances from C(6) to C(7) and C(8) which are 2·37 Å and 2·92 Å, respectively.

The arrangement of the molecules in the crystal as viewed in projection along the *c*-axis is shown in Fig. 4. The shorter intermolecular contacts are given in Table 4. None of these appears to be abnormal.

[5] Darwin and Hodgkin, *Nature*, 1950, **166**, 827; Fenimore, *J. Amer. Chem. Soc.*, 1950, **72**, 3226.
[6] Webster, *J.*, 1956, 2841.
[7] Johansson and Lipscomb, *Acta Cryst.*, 1958, **11**, 594; Thomas, Robertson, and Cox, *ibid.*, p. 599; Brockway and Anderson, *Trans. Faraday Soc.*, 1937, **33**, 1233.
[8] Ketelaar and Palmer, *J. Amer. Chem. Soc.*, 1937, **59**, 2629.

XUM

TABLE 3. *Measured and calculated values of the structure factors.*

h	k	l	F (meas)	F (calc)	α	h	k	l	F (meas)	F (calc)	α	h	k	l	F (meas)	F (calc)	α
2	0	0	14·8	16·8	180°	4	5	0	19·9	22·9	0°	9	13	0	7·7	8·0	270°
4	0	0	19·6	12·0	180	5	5	0	124·1	112·3	270						
6	0	0	42·4	56·4	180	6	5	0	71·3	79·8	180	4	14	0	6·9	7·5	180
8	0	0	107·1	116·1	180	7	5	0	4·7	4·0	270						
10	0	0	24·5	23·4	180	8	5	0	44·5	43·0	0						
12	0	0	43·0	49·1	0	9	5	0	9·6	5·8	270	2	0	1	68·7	86·3	270
14	0	0	28·4	29·5	0	10	5	0	60·6	68·2	0	3	0	1	94·1	100·5	90
18	0	0	32·7	31·2	180	11	5	0	18·0	16·2	90	4	0	1	35·8	35·6	90
20	0	0	10·4	11·4	180	12	5	0	38·7	35·9	180	5	0	1	131·0	197·0	270
22	0	0	11·5	6·6	0	13	5	0	34·6	28·3	270	6	0	1	83·6	83·6	90
24	0	0	27·0	19·3	180	14	5	0	11·5	8·1	0	7	0	1	53·0	59·8	270
						16	5	0	12·1	18·9	180	8	0	1	73·8	89·3	270
1	1	0	47·5	45·3	90	17	5	0	15·4	12·3	90	9	0	1	24·9	22·5	90
2	1	0	14·5	16·5	0	18	5	0	16·3	14·7	180	10	0	1	49·5	59·4	270
3	1	0	90·4	84·2	90	19	5	0	22·3	16·4	270	11	0	1	8·8	8·7	270
4	1	0	157·1	193·9	180	20	5	0	12·3	18·6	0	12	0	1	64·1	70·1	90
5	1	0	92·8	95·7	90	21	5	0	8·5	10·0	90	13	0	1	39·9	62·1	90
6	1	0	100·2	105·3	0	23	5	0	13·5	9·3	90	15	0	1	22·1	27·4	270
7	1	0	10·4	13·8	270												
8	1	0	43·8	31·4	180	0	6	0	10·7	4·8	180	1	1	1	125·1	101·4	286
9	1	0	105·2	122·9	270	1	6	0	74·8	74·9	90	2	1	1	125·2	126·3	252
10	1	0	6·3	8·6	0	2	6	0	74·2	75·9	180	3	1	1	119·2	104·3	218
11	1	0	8·4	12·7	270	3	6	0	48·8	37·8	270	4	1	1	104·4	98·6	193
12	1	0	66·1	55·7	0	4	6	0	40·4	44·0	0	5	1	1	81·3	82·1	165
14	1	0	16·1	23·6	180	5	6	0	47·0	52·4	270	6	1	1	83·6	92·1	288
15	1	0	8·3	2·3	90	6	6	0	67·0	75·1	0	7	1	1	28·6	38·8	237
16	1	0	26·6	23·8	180	8	6	0	29·7	34·6	180	8	1	1	26·0	30·4	51
17	1	0	38·3	46·4	90	9	6	0	11·5	10·4	270	9	1	1	92·4	102·4	115
18	1	0	33·7	34·2	0	10	6	0	19·6	21·5	0	10	1	1	13·7	11·8	69
19	1	0	10·2	3·5	270	12	6	0	28·3	35·9	180	11	1	1	43·2	59·4	343
23	1	0	9·1	3·1	90	13	6	0	46·1	51·4	90	12	1	1	61·1	68·5	35
						14	6	0	37·8	48·4	180	13	1	1	18·1	25·7	357
0	2	0	141·2	173·8	180	15	6	0	9·8	12·1	90	14	1	1	37·0	47·9	185
1	2	0	122·3	120·4	90	16	6	0	11·7	14·4	0	15	1	1	15·4	14·4	37
2	2	0	132·3	117·0	0	21	6	0	12·7	12·0	90	16	1	1	17·3	25·3	223
3	2	0	107·0	96·7	90							17	1	1	28·7	38·4	242
4	2	0	43·3	43·6	180	2	7	0	14·5	9·4	0	18	1	1	28·7	28·5	66
5	2	0	118·0	107·3	270	3	7	0	82·7	88·2	270	19	1	1	16·4	20·6	112
6	2	0	50·7	47·4	180	4	7	0	50·4	61·4	180	20	1	1	18 2	20·6	283
7	2	0	90·2	69·9	90	5	7	0	14·3	11·1	270						
8	2	0	20·0	16·8	180	6	7	0	12·2	9·9	0	0	2	1	154·0	131·7	180
9	2	0	61·4	58·0	270	7	7	0	38·6	38·9	90	1	2	1	99·1	81·6	25
10	2	0	12·3	11·5	0	8	7	0	35·7	31·3	0	2	2	1	130·0	108·5	65
11	2	0	4·1	6·9	270	9	7	0	24·7	23·4	90	3	2	1	76·9	67·9	201
12	2	0	14·7	22·6	0	10	7	0	19·0	15·0	180	4	2	1	91·1	73·2	98
13	2	0	77·2	86·1	90	12	7	0	32·2	38·5	0	5	2	1	115·9	97·1	175
14	2	0	9·4	26·7	0							6	2	1	45·6	37·2	195
16	2	0	36·4	32·7	180	0	8	0	70·3	68·4	180	7	2	1	76·0	94·3	317
17	2	0	34·4	34·3	270	1	8	0	37·0	32·8	270	8	2	1	109·5	120·0	332
20	2	0	14·0	7·5	0	3	8	0	18·6	26·0	90	9	2	1	39·2	38·7	4
24	2	0	10·4	10·5	0	4	8	0	36·3	31·0	0	10	2	1	47·6	52·8	174
						5	8	0	18·7	22·8	270	11	2	1	53·0	60·3	87
1	3	0	83·2	71·8	270	7	8	0	21·1	26·7	90	12	2	1	38·1	29·9	246
2	3	0	71·9	76·3	180	8	8	0	19·2	24·0	0	13	2	1	16·3	11·7	228
3	3	0	133·8	113·5	90	9	8	0	10·6	8·8	270	14	2	1	23·7	22·5	34
4	3	0	181·1	169·5	180	11	8	0	10·9	6·5	270	16	2	1	15·7	17·7	151
5	3	0	113·9	100·7	90	12	8	0	18·4	22·2	180	18	2	1	21·8	35·5	3
6	3	0	89·5	72·9	180	14	8	0	19·1	18·9	180	19	2	1	17·9	17·4	242
7	3	0	63·0	58·7	270	15	8	0	19·0	19·3	270						
8	3	0	113·3	127·8	0	18	8	0	13·1	15·0	0	0	3	1	121·4	95·5	90
9	3	0	9·1	2·2	90	19	8	0	11·1	11·8	90	1	3	1	49·2	47·2	302
10	3	0	24·1	27·2	0	20	8	0	9·7	5·5	180	2	3	1	162·4	131·0	169
11	3	0	42·0	46·0	270	21	8	0	11·0	10·7	270	3	3	1	106·4	87·0	264
12	3	0	30·5	23·0	180							4	3	1	94·9	76·7	308
13	3	0	29·7	26·5	90							5	3	1	51·2	44·9	176
14	3	0	24·3	19·8	180	2	9	0	19·0	24·2	0	6	3	1	60·6	62·3	196
16	3	0	9·6	4·2	180	5	9	0	30·9	30·1	270	7	3	1	66·9	55·9	25
17	3	0	19·9	22·9	270	9	9	0	45·2	50·7	90	8	3	1	33·5	32·9	299
18	3	0	21·2	28·9	180	10	9	0	11·0	5·8	180	9	3	1	41·6	42·3	57
19	3	0	32·2	30·2	90	11	9	0	11·0	6·0	270	10	3	1	63·5	64·6	335
20	3	0	10·2	5·4	180	12	9	0	10·5	11·8	180	11	3	1	37·9	33·9	149
25	3	0	11·3	12·3	90	13	9	0	16·4	17·2	270	12	3	1	55·8	58·7	159
26	3	0	9·2	7·9	180	14	9	0	10·5	9·4	0	13	3	1	42·9	49·2	346
						15	9	0	10·7	10·8	90	14	3	1	47·4	53·3	58
0	4	0	28·2	21·5	0							17	3	1	16·0	13·9	178
1	4	0	137·3	135·7	90	0	10	0	32·7	33·9	180	18	3	1	18·5	25·7	255
2	4	0	33·8	39·6	0	1	10	0	10·7	6·8	270						
3	4	0	52·5	57·4	270	2	10	0	13·2	10·0	0	0	4	1	53·0	46·6	0
4	4	0	24·5	19·1	180	5	10	0	24·7	29·2	90	1	4	1	84·0	68·4	204
5	4	0	27·9	19·4	270	6	10	0	12·2	15·8	0	2	4	1	132·5	103·3	206
6	4	0	45·0	36·8	180	8	10	0	11·9	17·3	0	3	4	1	40·5	31·5	235
7	4	0	105·8	97·1	270	12	10	0	10·8	8·7	180	4	4	1	27·6	24·9	7
8	4	0	24·1	27·0	0	13	10	0	10·7	13·3	270	5	4	1	25·4	28·7	59
9	4	0	29·6	29·1	270							6	4	1	152·4	125·3	13
10	4	0	59·2	62·2	180	4	11	0	25·7	33·7	0	7	4	1	24·9	18·6	336
11	4	0	45·8	60·6	90	8	11	0	22·1	22·3	180	8	4	1	27·3	29·0	132
14	4	0	31·9	30·1	0	10	11	0	16·1	12·0	180	9	4	1	66·0	70·7	347
15	4	0	17·2	19·6	90							10	4	1	14·7	13·1	109
21	4	0	11·6	10·8	90	1	12	0	14·2	17·2	270	11	4	1	34·6	35·1	32
						5	12	0	11·3	9·8	90	12	4	1	36·8	36·8	150
1	5	0	8·2	3·6	90	8	12	0	10·7	13·9	180	13	4	1	14·9	23·5	229
2	5	0	73·5	68·4	180	13	12	0	8·2	9·8	270	14	4	1	16·8	26·4	155
3	5	0	24·3	30·5	270	17	12	0	3·7	5·4	90	15	4	1	18·0	31·5	107

XUM

TABLE 3. (*Continued.*)

h	k	l	F (meas)	F (calc)	α
16	4	1	15·9	21·7	327°
18	4	1	16·6	7·8	216
0	5	1	111·7	96·4	90
1	5	1	53·6	44·4	182
2	5	1	28·0	26·1	346
3	5	1	48·0	44·9	303
4	5	1	37·4	39·1	248
5	5	1	72·0	57·0	324
6	5	1	28·7	30·9	319
7	5	1	64·1	55·2	106
8	5	1	21·1	28·2	224
9	5	1	22·5	31·2	285
10	5	1	23·6	30·6	145
11	5	1	48·8	51·3	68
12	5	1	15·2	16·1	52
13	5	1	24·3	28·6	202
15	5	1	31·7	42·3	256
16	5	1	17·8	17·5	307
0	6	1	42·0	35·4	180
1	6	1	64·6	52·5	338
3	6	1	57·9	51·5	128
4	6	1	44·7	41·4	285
5	6	1	48·0	50·8	196
6	6	1	56·0	48·4	12
7	6	1	48·3	43·2	84
9	6	1	23·5	30·2	19
10	6	1	36·0	37·0	111
11	6	1	72·7	55·8	240
13	6	1	43·0	30·9	133
15	6	1	15·7	23·6	310
1	7	1	36·4	33·4	238
2	7	1	74·1	69·8	7
3	7	1	15·0	22·0	201
5	7	1	27·7	35·2	50
7	7	1	39·9	45·8	318
9	7	1	29·4	37·9	83
10	7	1	24·5	33·1	191
11	7	1	15·9	5·9	226
13	7	1	16·2	20·9	39
2	8	1	17·0	20·9	321
3	8	1	16·4	22·8	264
4	8	1	25·0	23·0	241
5	8	1	29·3	32·0	69
6	8	1	35·8	36·1	219
7	8	1	15·8	20·1	63
8	8	1	51·4	54·3	68
9	8	1	15·5	18·0	203
10	8	1	21·0	25·1	158
1	9	1	44·6	43·4	181
2	9	1	17·5	12·7	248
3	9	1	20·1	26·9	20
4	9	1	17·0	24·7	16
6	9	1	28·6	31·6	154
8	9	1	20·7	20·4	134
0	10	1	16·0	23·7	0
3	10	1	20·9	25·9	324
5	10	1	16·0	18·7	54
0	11	1	21·8	22·9	270
1	11	1	18·0	21·0	80
1	0	2	51·7	62·0	0
2	0	2	74·5	72·6	0
3	0	2	126·7	153·6	180
4	0	2	57·8	42·4	180
5	0	2	52·7	37·7	180
6	0	2	26·7	25·1	0
7	0	2	91·9	87·9	0
8	0	2	78·8	67·8	0
10	0	2	90·6	80·1	180
11	0	2	58·3	61·1	0
12	0	2	7·3	7·2	180
13	0	2	10·3	8·7	180
14	0	2	72·8	60·2	0
15	0	2	48·6	58·2	180
16	0	2	34·9	40·3	180
19	0	2	12·2	9·7	0
20	0	0	9·1	9·8	180
21	0	2	8·3	2·1	0
0	1	2	64·5	48·3	90
1	1	2	74·7	62·1	259
2	1	2	101·7	95·1	108
3	1	2	24·4	30·5	37
4	1	2	141·3	124·7	356
5	1	2	56·3	49·3	187
6	1	2	126·2	130·3	244
7	1	2	55·8	60·9	308°
8	1	2	56·7	48·2	217
9	1	2	38·7	30·9	120
10	1	2	36·1	36·3	91
11	1	2	61·3	68·3	176
12	1	2	41·7	50·6	102
13	1	2	39·6	33·8	13
14	1	2	12·0	15·9	70
15	1	2	15·3	14·9	160
16	1	2	22·9	15·3	201
17	1	2	7·7	3·1	218
18	1	2	8·8	4·4	181
19	1	2	8·6	15·2	30
20	1	2	30·2	34·1	331
22	1	2	15·5	13·3	161
27	1	2	7·0	1·6	262
0	2	2	53·1	56·2	180
1	2	2	125·7	130·0	149
2	2	2	147·5	154·4	243
3	2	2	111·5	96·0	230
4	2	2	87·0	72·8	355
5	2	2	69·6	53·0	33
6	2	2	56·6	54·3	298
7	2	2	18·1	14·6	110
8	2	2	58·0	61·3	94
9	2	2	56·1	52·4	339
10	2	2	44·8	58·0	55
11	2	2	41·8	47·6	46
12	2	2	7·3	5·4	109
13	2	2	15·3	22·2	239
14	2	2	27·2	29·3	203
15	2	2	32·9	35·9	143
16	2	2	22·4	26·5	275
17	2	2	13·6	22·9	194
18	2	2	8·9	12·5	220
19	2	2	8·2	6·8	323
20	2	2	10·0	11·5	61
21	2	2	11·0	12·9	98
22	2	2	9·8	7·3	289
23	2	2	9·1	11·0	251
0	3	2	83·1	85·6	90
1	3	2	77·0	78·3	169
2	3	2	32·8	25·3	0
3	3	2	85·9	73·6	262
4	3	2	28·6	25·3	126
5	3	2	83·5	70·7	350
6	3	2	42·3	33·8	184
7	3	2	107·0	114·3	30
8	3	2	43·3	47·6	297
9	3	2	74·2	61·6	276
10	3	2	37·9	40·4	88
11	3	2	44·1	46·1	159
12	3	2	31·4	32·3	221
13	3	2	43·5	47·9	157
14	3	2	14·9	18·8	304
15	3	2	23·5	27·0	248
16	3	2	8·6	5·2	52
17	3	2	15·3	18·0	104
18	3	2	32·9	32·6	246
19	3	2	11·7	16·2	350
20	3	2	12·1	11·3	185
22	3	2	9·7	11·0	28
0	4	2	141·1	123·3	0
1	4	2	59·4	58·8	229
2	4	2	86·0	70·1	263
3	4	2	72·3	70·7	57
4	4	2	94·1	97·3	243
5	4	2	19·3	22·0	270
6	4	2	45·4	49·1	80
7	4	2	33·5	34·6	96
8	4	2	32·3	28·3	170
9	4	2	31·1	27·2	50
10	4	2	21·4	25·3	60
11	4	2	15·4	20·9	258
12	4	2	36·2	38·7	104
13	4	2	15·5	12·7	114
14	4	2	43·5	45·3	267
15	4	2	23·7	24·7	301
16	4	2	22·7	29·8	286
17	4	2	9·0	3·2	40
18	4	2	15·0	11·8	112
21	4	2	8·5	9·8	289
0	5	2	59·6	54·3	270
1	5	2	36·4	37·4	207
2	5	2	47·4	50·0	341
3	5	2	75·4	89·0	174
4	5	2	38·2	37·5	141
5	5	2	76·3	82·1	339
6	5	2	40·0	43·7	28
7	5	2	41·8	48·3	308°
8	5	2	39·0	37·0	87
9	5	2	38·5	34·8	117
10	5	2	24·0	29·7	227
11	5	2	21·0	24·5	217
12	5	2	19·8	20·5	325
13	5	2	21·1	24·1	229
14	5	2	10·4	18·2	215
15	5	2	11·0	13·7	62
16	5	2	11·8	13·6	281
17	5	2	11·7	11·2	18
18	5	2	9·2	16·3	58
19	5	2	10·3	10·2	314
20	5	2	9·4	8·5	184
21	5	2	8·7	10·8	12
0	6	2	90·5	85·0	180
1	6	2	85·8	88·7	1
2	6	2	44·9	51·3	291
3	6	2	39·5	37·6	326
4	6	2	8·2	11·2	290
5	6	2	26·6	24·2	3
6	6	2	7·7	9·6	176
7	6	2	27·3	32·0	69
8	6	2	30·3	31·2	18
9	6	2	41·6	53·0	207
10	6	2	24·5	33·5	126
11	6	2	22·8	22·8	199
12	6	2	8·6	6·3	56
13	6	2	23·9	19·5	90
14	6	2	13·8	13·5	259
15	6	2	16·6	13·2	64
16	6	2	18·5	21·0	194
17	6	2	14·1	19·8	328
18	6	2	9·1	8·0	43
24	6	2	6·9	7·5	14
25	6	2	6·2	5·7	225
0	7	2	41·3	44·8	270
1	7	2	20·4	18·5	244
2	7	2	25·2	29·4	222
3	7	2	22·8	22·8	47
4	7	2	35·4	31·2	339
5	7	2	12·9	16·0	116
6	7	2	43·3	43·3	122
7	7	2	25·3	29·0	352
8	7	2	27·5	33·4	54
10	7	2	31·1	32·6	254
11	7	2	21·7	24·3	190
12	7	2	24·8	23·6	249
13	7	2	18·8	18·7	25
17	7	2	14·2	13·9	269
19	7	2	8·5	11·3	35
20	7	2	9·9	11·3	48
0	8	2	9·0	8·1	0
1	8	2	15·8	12·6	336
2	8	2	10·7	13·3	293
3	8	2	68·1	61·6	340
4	8	2	27·4	26·6	53
5	8	2	18·4	22·8	49
6	8	2	22·7	21·8	219
7	8	2	8·7	13·8	241
8	8	2	10·0	15·4	198
9	8	2	8·5	5·8	157
10	8	2	9·4	13·2	320
11	8	2	19·4	22·0	134
12	8	2	8·7	10·0	239
13	8	2	15·2	19·9	287
14	8	2	8·7	4·6	133
15	8	2	14·7	21·3	345
0	9	2	12·6	4·5	270
1	9	2	44·2	44·9	59
2	9	2	20·9	27·9	295
3	9	2	14·9	16·6	323
4	9	2	14·0	10·4	46
5	9	2	15·7	20·2	244
6	9	2	43·2	48·9	95
7	9	2	18·0	20·1	172
8	9	2	8·7	5·8	105
9	9	2	8·7	4·8	221
10	9	2	11·4	7·8	3
11	9	2	10·3	9·1	18
12	9	2	11·0	14·3	229
0	10	2	14·6	18·7	0
1	10	2	11·4	11·8	356
2	10	2	33·9	31·5	92
3	10	2	14·9	21·6	39
4	10	2	17·9	12·2	108
5	10	2	9·6	15·7	266
6	10	2	15·4	18·8	52

XUM

TABLE 3. (*Continued.*)

h	*k*	*l*	*F* (meas)	*F* (calc)	α
7	10	2	10·3	7·3	144°
16	10	2	8·6	12·5	77
17	10	2	10·2	5·8	245
0	11	2	9·4	2·9	90
1	11	2	10·5	16·1	336
6	11	2	9·9	11·6	348
8	11	2	13·4	8·4	142
11	11	2	12·9	14·4	343
12	11	2	11·1	11·5	0
13	11	2	8·0	2·0	291
2	12	2	15·2	18·4	60
4	12	2	8·7	9·6	77
7	12	2	8·0	5·9	25
8	13	2	9·0	4·2	323
3	14	2	6·0	5·5	181
2	0	3	108·7	139·1	270
3	0	3	12·2	12·6	270
4	0	3	58·0	47·9	90
5	0	3	66·8	42·7	270
6	0	3	8·0	10·2	90
7	0	3	88·5	74·0	270
8	0	3	30·4	29·4	90
9	0	3	48·4	38·3	270
10	0	3	21·6	35·3	90
11	0	3	38·9	48·3	90
12	0	3	47·4	52·3	270
13	0	3	31·8	14·3	270
15	0	3	38·6	38·2	90
16	0	3	45·5	44·1	270
19	0	3	16·8	24·1	270
20	0	3	22·8	25·9	90
0	1	3	51·7	58·9	90
1	1	3	61·3	69·9	168
2	1	3	147·0	139·2	192
3	1	3	107·0	86·7	323
4	1	3	37·2	28·3	116
5	1	3	23·0	22·6	287
6	1	3	57·0	42·9	121
7	1	3	52·9	57·2	30
8	1	3	68·1	60·5	277
9	1	3	29·5	23·4	238
10	1	3	69·9	61·3	70
11	1	3	60·8	59·6	140
12	1	3	28·2	32·1	297
13	1	3	23·0	17·8	130
14	1	3	27·8	33·0	238
15	1	3	43·4	37·2	259
16	1	3	18·9	25·0	124
17	1	3	15·1	20·3	326
18	1	3	9·9	7·7	25
19	1	3	12·5	15·4	15
20	1	3	16·7	13·0	338
21	1	3	10·0	7·7	179
22	1	3	8·9	4·7	292
26	1	3	7·8	6·3	41
0	2	3	35·6	28·4	180
1	2	3	31·4	27·6	177
2	2	3	109·6	82·4	134
3	2	3	111·4	99·3	27
4	2	3	79·0	68·8	285
5	2	3	44·2	41·8	322
6	2	3	90·3	84·1	12
7	2	3	78·0	80·1	220
8	2	3	37·0	39·3	89
9	2	3	37·9	31·4	45
10	2	3	27·8	23·1	66
11	2	3	34·6	41·5	146
13	2	3	12·9	17·1	65
14	2	3	29·0	30·8	264
15	2	3	41·5	48·9	342
16	2	3	21·6	18·8	17
17	2	3	16·1	12·3	150
19	2	3	10·5	9·0	287
20	2	3	10·1	10·6	11
21	2	3	9·5	8·5	235
0	3	3	39·5	36·2	270
1	3	3	46·1	41·8	324
2	3	3	50·2	46·5	321
3	3	3	102·9	95·9	212
4	3	3	42·9	52·1	138
5	3	3	47·7	49·9	9
6	3	3	40·5	41·9	55
7	3	3	32·9	25·1	205
8	3	3	22·9	20·0	107
9	3	3	29·5	27·5	161°
10	3	3	48·3	44·5	275
11	3	3	32·4	38·2	72
12	3	3	44·3	39·6	306
13	3	3	26·7	28·5	185
14	3	3	13·0	11·4	176
15	3	3	49·9	34·9	344
16	3	3	10·5	10·4	131
17	3	3	12·3	14·1	8
18	3	3	10·9	13·1	36
19	3	3	9·1	11·1	115
20	3	3	14·8	13·4	119
21	3	3	16·0	16·0	17
23	3	3	9·9	14·1	141
0	4	3	7·5	7·3	180
1	4	3	54·9	58·0	338
2	4	3	22·4	17·1	212
3	4	3	9·2	6·9	174
4	4	3	18·4	21·8	253
5	4	3	57·0	47·1	291
6	4	3	95·1	71·4	39
7	4	3	21·2	15·2	107
8	4	3	45·0	51·9	356
9	4	3	79·7	86·2	169
10	4	3	49·8	54·0	191
11	4	3	32·8	25·8	356
12	4	3	16·1	16·7	139
13	4	3	28·4	24·7	19
14	4	3	13·2	11·4	297
15	4	3	15·9	10·2	129
16	4	3	17·2	18·2	182
17	4	3	10·0	19·8	24
18	4	3	9·1	11·2	14
19	4	3	10·0	11·1	144
20	4	3	10·4	12·3	349
0	5	3	79·0	82·3	270
1	5	3	88·9	65·8	270
3	5	3	58·6	61·5	312
4	5	3	28·9	29·1	33
5	5	3	23·9	28·3	160
6	5	3	10·0	12·8	172
7	5	3	8·8	15·2	192
8	5	3	33·1	45·1	121
9	5	3	27·3	34·2	84
10	5	3	26·4	32·2	234
11	5	3	27·2	22·4	50
12	5	3	14·7	18·5	252
13	5	3	14·5	17·0	353
15	5	3	20·0	21·6	231
17	5	3	10·5	12·9	265
18	5	3	18·2	27·7	93
21	5	3	9·3	9·4	179
0	6	3	17·3	19·4	180
1	6	3	28·5	29·6	333
2	6	3	15·0	9·9	61
3	6	3	38·5	33·4	297
4	6	3	70·2	71·8	91
5	6	3	40·4	46·0	107
6	6	3	23·6	30·9	297
7	6	3	37·8	37·5	96
8	6	3	35·3	34·6	312
10	6	3	9·2	5·0	218
11	6	3	12·7	12·3	133
12	6	3	26·2	28·4	261
13	6	3	12·6	16·0	290
14	6	3	13·8	23·6	107
15	6	3	17·7	22·7	16
0	7	3	28·7	30·9	90
1	7	3	31·0	30·1	5
2	7	3	31·4	38·5	336
4	7	3	30·1	26·5	36
5	7	3	41·4	42·4	164
6	7	3	21·8	27·3	124
7	7	3	13·8	17·3	85
8	7	3	30·0	35·1	272
9	7	3	8·6	16·2	289
10	7	3	8·8	12·1	148
11	7	3	9·8	14·5	125
12	7	3	30·1	31·2	194
13	7	3	18·0	25·2	359
14	7	3	10·1	19·7	341
15	7	3	10·5	8·3	277
16	7	3	20·6	23·7	48
17	7	3	11·0	11·4	162
0	8	3	18·4	19·8	0
1	8	3	17·7	28·8	207
2	8	3	29·1	33·8	107
4	8	3	16·0	17·7	178
5	8	3	25·7	27·9	50°
7	8	3	19·9	27·6	138
8	8	3	24·3	25·3	190
9	8	3	11·3	16·7	18
10	8	3	15·5	22·5	254
11	8	3	19·1	22·9	274
12	8	3	13·3	15·2	82
0	9	3	19·2	19·8	90
1	9	3	19·4	18·2	46
2	9	3	15·9	19·0	23
3	9	3	12·8	15·6	146
4	9	3	10·4	11·2	217
6	9	3	11·1	12·7	268
7	9	3	23·6	28·7	199
10	9	3	10·5	16·7	182
11	9	3	18·5	26·3	350
15	9	3	8·7	5·5	25
3	10	3	20·8	21·9	211
5	10	3	16·3	18·4	198
6	10	3	16·0	19·5	162
7	10	3	15·3	18·1	52
8	10	3	15·4	13·2	263
11	10	3	11·7	13·7	315
12	10	3	10·0	12·3	53
3	11	3	10·4	13·6	102
4	11	3	5·5	3·1	235
7	11	3	10·4	7·3	304
7	12	3	11·3	6·4	323
8	12	3	8·7	6·0	134
1	13	3	7·7	9·2	130
1	0	4	32·1	55·7	180
2	0	4	79·8	93·2	180
3	0	4	7·7	15·0	0
5	0	1	32·4	22·4	0
6	0	4	39·7	32·8	0
7	0	4	86·9	62·1	180
8	0	4	48·9	42·8	0
9	0	4	84·1	69·2	0
10	0	4	14·3	8·5	180
12	0	4	34·5	35·4	180
13	0	4	12·1	2·6	0
14	0	4	12·2	19·0	180
15	0	4	30·4	28·9	0
16	0	4	19·5	16·0	0
17	0	4	21·9	25·3	180
18	0	4	13·7	21·8	0
1	1	4	33·8	46·6	338
2	1	4	37·6	38·6	333
3	1	4	149·3	129·1	212
4	1	4	75·1	57·8	59
5	1	4	87·7	71·3	307
6	1	4	62·9	47·1	24
7	1	4	66·2	49·9	135
8	1	4	50·8	52·4	210
9	1	4	70·5	67·6	116
10	1	4	44·5	43·3	133
11	1	4	19·5	22·4	28
12	1	4	10·3	15·5	243
13	1	4	12·2	13·8	251
14	1	4	14·1	13·8	306
15	1	4	19·9	23·9	322
16	1	4	28·2	23·9	127
18	1	4	19·3	18·1	352
19	1	4	12·7	11·2	194
21	1	4	12·9	15·6	30
0	2	4	118·8	115·5	180
1	2	4	74·7	73·1	279
2	2	4	52·1	44·9	101
3	2	4	11·5	9·4	188
4	2	4	68·4	61·8	346
5	2	4	53·0	55·6	35
6	2	4	60·6	58·0	45
7	2	4	38·1	40·8	60
8	2	4	8·5	9·1	346
9	2	4	61·6	54·3	188
10	2	4	27·6	26·4	304
11	2	4	39·4	39·0	317
12	2	4	46·6	50·9	120
14	2	4	33·0	35·3	232
15	2	4	19·4	21·9	173
16	2	4	11·1	9·9	68
20	2	4	11·4	15·0	277
0	3	4	30·9	35·6	270
1	3	4	22·7	25·5	260

XUM

TABLE 3. (*Continued.*)

h	k	l	F (meas)	F (calc)	α
2	3	4	92·6	70·7	66°
3	3	4	17·7	15·0	240
4	3	4	50·7	49·4	355
5	3	4	10·4	14·7	296
6	3	4	46·4	48·5	280
7	3	4	24·8	16·9	359
8	3	4	35·9	37·3	121
9	3	4	12·0	8·0	78
10	3	4	54·6	55·5	233
12	3	4	12·4	9·4	309
13	3	4	15·4	13·1	170
14	3	4	14·7	20·0	48
15	3	4	18·7	15·2	214
16	3	4	26·3	31·0	330
17	3	4	16·2	13·9	226
20	3	4	13·0	13·3	207
0	4	4	7·3	19·5	0
1	4	4	78·7	81·2	299
2	4	4	70·9	59·1	281
3	4	4	37·4	32·5	106
4	4	4	48·0	52·1	93
5	4	4	48·1	48·2	118
6	4	4	40·0	34·3	247
7	4	4	31·6	36·1	57
8	4	4	39·6	32·2	276
9	4	4	25·7	26·3	126
10	4	4	20·6	14·1	161
12	4	4	13·8	12·0	248
13	4	4	44·1	47·0	282
14	4	4	20·1	21·3	49
15	4	4	11·2	11·7	217
16	4	4	23·5	20·0	266
17	4	4	19·2	22·9	52
22	4	4	10·6	10·2	268
0	5	4	15·4	28·0	90
1	5	4	25·6	25·5	49
2	5	4	42·1	40·5	317
3	5	4	46·6	46·7	64
4	5	4	65·9	69·2	10
5	5	4	48·2	55·5	174
6	5	4	9·2	15·0	91
7	5	4	10·9	9·8	328
8	5	4	47·1	49·9	205
10	5	4	24·9	28·7	145
11	5	4	21·2	25·8	188
13	5	4	26·4	36·2	3
14	5	4	16·4	18·8	295
15	5	4	12·1	14·1	117
17	5	4	14·8	12·7	151
0	6	4	36·2	34·4	0
1	6	4	37·1	39·3	194
2	6	4	10·0	5·2	353
3	6	4	17·9	21·3	325
4	6	4	22·5	20·4	166
5	6	4	24·5	22·5	80
6	6	4	11·1	12·9	182
7	6	4	21·0	23·4	142
8	6	4	17·1	14·4	172
9	6	4	36·7	40·2	357
11	6	4	15·2	16·8	240
12	6	4	19·5	25·8	14
13	6	4	12·6	12·1	249
15	6	4	16·7	21·5	351
17	6	4	11·9	16·2	159
0	7	4	36·9	39·0	90
1	7	4	18·2	13·6	56
2	7	4	37·4	44·4	162
4	7	4	18·2	15·9	285
5	7	4	40·7	50·6	52
8	7	4	14·3	13·8	233
9	7	4	38·5	43·3	285
10	7	4	11·9	12·7	221
11	7	4	11·4	14·4	308
0	8	4	39·6	41·5	0
1	8	4	13·3	13·2	335
2	8	4	11·7	17·7	38
3	8	4	15·3	19·1	119
4	8	4	18·3	21·9	217
6	8	4	26·5	32·6	148
7	8	4	13·7	14·1	341
8	8	4	13·2	15·4	216
10	8	4	13·8	14·5	306
12	8	4	15·7	20·8	52
14	8	4	12·8	13·6	322
2	9	4	14·3	19·6	101
3	9	4	14·8	20·9	64
4	9	4	17·2	16·2	211
8	9	4	12·0	16·2	53°
9	9	4	13·1	12·3	250
10	9	4	12·4	15·7	304
1	10	4	13·7	19·1	44
4	10	4	14·1	16·3	140
5	10	4	17·6	20·2	217
7	10	4	12·2	13·3	327
1	11	4	15·5	7·8	207
3	11	4	11·7	8·4	18
9	11	4	11·5	3·8	300
1	12	4	10·7	15·8	131
3	0	5	31·3	41·2	270
4	0	5	63·6	82·1	270
5	0	5	28·4	23·8	90
6	0	5	13·4	22·9	90
7	0	5	36·4	32·2	90
8	0	5	40·7	33·0	90
9	0	5	8·5	8·6	90
10	0	5	9·4	2·1	270
11	0	5	43·1	26·4	270
12	0	5	59·3	46·7	90
13	0	5	17·1	21·6	270
14	0	5	30·6	35·9	270
15	0	5	18·3	12·3	90
16	0	5	13·0	8·7	90
17	0	5	11·7	15·7	90
18	0	5	17·0	13·8	270
0	1	5	28·1	49·3	270
1	1	5	23·8	32·4	138
2	1	5	24·0	31·9	59
3	1	5	25·6	20·5	250
4	1	5	60·1	61·6	40
5	1	5	65·3	65·8	25
6	1	5	33·7	35·1	232
7	1	5	9·9	5·2	17
8	1	5	78·6	62·5	123
9	1	5	37·1	25·4	304
10	1	5	40·3	34·9	202
11	1	5	26·6	18 7	2
12	1	5	16·2	12·6	7
13	1	5	48·7	42·7	171
14	1	5	17·2	16·9	319
15	1	5	17·7	11·6	221
16	1	5	16·0	14·9	306
17	1	5	11·7	10·2	355
18	1	5	15·4	16·9	78
19	1	5	11·6	5·0	149
20	1	5	11·4	10·9	261
0	2	5	46·0	47·3	0
1	2	5	63·0	67·3	320
2	2	5	12·5	11·8	13
3	2	5	34·4	28·8	95
4	2	5	39·4	36·9	258
5	2	5	21·6	18·5	90
6	2	5	68·1	47·6	239
7	2	5	42·5	36·1	19
8	2	5	22·5	21·4	105
9	2	5	59·4	60·0	181
10	2	5	50·1	52·4	52
12	2	5	29·6	29·7	301
13	2	5	14·1	14·5	287
14	2	5	26·2	26·9	90
15	2	5	19·0	16·1	215
17	2	5	20·0	24·5	22
0	3	5	59·6	63·6	270
1	3	5	43·4	47·3	154
2	3	5	34·0	36·9	339
3	3	5	69·5	65·5	35
4	3	5	13·3	14·3	75
5	3	5	65·7	54·2	152
6	3	5	50·3	43·4	67
7	3	5	45·2	42·3	322
8	3	5	17·3	13·8	115
9	3	5	26·7	31·9	304
10	3	5	10·3	5·7	146
11	3	5	32·8	36·3	199
12	3	5	16·1	19·0	256
13	3	5	11·0	10·3	13
14	3	5	14·9	14·0	281
15	3	5	29·9	30·2	104
16	3	5	12·2	11·0	355
17	3	5	13·2	11·3	124
0	4	5	42·7	49·8	0
1	4	5	39·8	38·5	182
2	4	5	33·0	34·4	319
3	4	5	43·5	40·0	3°
4	4	5	45·4	39·7	147
5	4	5	65·7	59·7	356
6	4	5	31·8	28·7	219
7	4	5	44·6	46·1	162
8	4	5	9·3	7·2	251
9	4	5	16·4	18·3	213
10	4	5	16·7	18·7	218
11	4	5	17·8	19·6	168
12	4	5	28·1	31·3	337
13	4	5	12·8	7·0	160
14	4	5	12·1	16·8	21
15	4	5	12·7	14·3	54
16	4	5	11·7	10·7	198
19	4	5	13·5	16·0	347
1	5	5	19·2	12·7	4
2	5	5	46·5	51·5	222
3	5	5	33·5	35·5	115
4	5	5	27·8	29·8	107
5	5	5	17·1	16·3	33
6	5	5	10·4	12·9	116
7	5	5	32·7	26·4	205
9	5	5	16·5	16·7	246
10	5	5	37·7	35·8	86
11	5	5	12·7	17·6	15
12	5	5	12·9	16·8	257
13	5	5	18·9	16·2	76
14	5	5	14·6	18·9	260
16	5	5	18·3	19·6	128
1	6	5	13·4	15·0	71
2	6	5	21·9	31·2	65
3	6	5	18·7	23·1	310
4	6	5	12·6	14·4	229
5	6	5	22·8	24·3	345
6	6	5	24·0	24·9	118
7	6	5	11·4	13·4	251
8	6	5	25·5	24·8	237
9	6	5	12·3	9·8	89
10	6	5	22·3	27·2	312
11	6	5	11·6	18·4	90
12	6	5	15·0	22·0	60
0	7	5	36·7	42·9	270
1	7	5	37·0	40·5	26
2	7	5	10·5	11·3	94
3	7	5	19·0	25·4	177
4	7	5	20·3	19·1	180
5	7	5	18·0	14·2	118
6	7	5	11·4	15·7	220
8	7	5	20·7	25·7	38
9	7	5	23·4	25·2	228
14	7	5	12·9	11·3	179
1	8	5	17·1	18·5	58
3	8	5	13·1	12·6	141
4	8	5	22·0	24·6	100
5	8	5	24·2	22·0	249
7	8	5	15·0	21·0	324
9	8	5	15·4	21·4	164
11	8	5	11·0	12·3	24
13	9	5	10·6	18·7	337
3	10	5	13·1	12·9	239
0	11	5	11·5	15·4	90
1	0	6	64·4	90·5	0
2	0	6	15·4	19·0	180
3	0	6	22·0	20·2	0
4	0	6	16·0	13·6	180
5	0	6	8·4	15·0	180
6	0	6	12·6	8·7	180
7	0	6	15·3	8·4	0
8	0	6	29·5	34·5	180
9	0	6	47·0	42·9	180
10	0	6	31·0	24·4	0
11	0	6	14·5	9·5	180
16	0	6	16·9	16·8	0
17	0	6	12·9	16·4	0
0	1	6	23·0	50·8	270
1	1	6	22·5	36·2	58
2	1	6	22·5	22·0	348
3	1	6	28·6	28·4	37
4	1	6	20·9	25·1	133
5	1	6	61·2	58·9	193
6	1	6	65·0	43·5	44
7	1	6	11·7	5·8	163
8	1	6	41·2	31·7	103
9	1	6	9·1	3·8	260

TABLE 3. (*Continued.*)

h	k	l	F (meas)	F (calc)	α	h	k	l	F (meas)	F (calc)	α	h	k	l	F (meas)	F (calc)	α
10	1	6	18·6	18·3	252°	18	5	6	10·2	8·2	14°	0	2	7	9·7	21·1	180°
11	1	6	18·8	12·9	197	19	5	6	9·2	14·4	185	1	2	7	21·0	31·6	202
12	1	6	28·7	29·8	319							2	2	7	37·8	44·1	45
13	1	6	36·3	35·3	354	0	6	6	18·2	16·5	0	3	2	7	19·3	20·1	218
14	1	6	10·6	11·6	224	1	6	6	14·9	21·7	11	4	2	7	10·7	10·5	313
15	1	6	11·8	6·9	22	2	6	6	27·0	25·7	95	5	2	7	25·5	17·1	95
16	1	6	11·9	9·9	219	3	6	6	36·2	33·3	162	6	2	7	50·6	38·9	197
17	1	6	12·4	11·2	194	5	6	6	12·7	8·0	230	7	2	7	14·4	12·3	205
18	1	6	12·7	16·5	67	6	6	6	20·2	23·4	351	9	2	7	27·9	20·9	11
19	1	6	11·5	11·8	292	7	6	6	20·7	24·4	350	10	2	7	18·0	17·4	239
						8	6	6	21·2	18·1	190	13	2	7	17·8	14·4	228
0	2	6	21·3	25·5	180	11	6	6	11·9	11·8	345	14	2	7	13·7	12·3	47
1	2	6	7·9	4·9	238	14	6	6	10·6	8·4	64						
2	2	6	26·2	22·4	28	15	6	6	13·1	15·9	191	0	3	7	21·2	23·2	90
3	2	6	26·8	35·9	11							1	3	7	39·3	38·2	63
4	2	6	49·2	50·1	76	0	7	6	16·2	20·5	90	2	3	7	12·6	11·6	133
5	2	6	51·7	48·8	335	1	7	6	12·6	15·9	246	3	3	7	20·7	18·3	112
6	2	6	45·2	39·1	228	2	7	6	26·2	29·7	101	4	3	7	23·7	23·0	345
7	2	6	24·2	20·1	186	4	7	6	28·1	27·2	224	5	3	7	8·6	7·1	62
9	2	6	24·8	18·9	159	5	7	6	16·0	17·3	143	6	3	7	47·1	37·7	208
10	2	6	16·1	13·9	296	6	7	6	20·6	24·5	292	7	3	7	12·6	10·5	201
11	2	6	10·8	13·4	200	9	7	6	10·3	12·9	302	8	3	7	9·5	8·0	289
12	2	6	28·5	22·9	289	12	7	6	10·6	18·0	38	10	3	7	21·8	15·9	54
13	2	6	11·0	6·4	76							11	3	7	26·1	22·8	311
14	2	6	18·9	19·1	99	1	8	6	18·3	21·8	172	12	3	7	23·2	25·5	145
15	2	6	22·8	24·4	311	2	8	6	16·9	15·7	253	13	3	7	15·6	15·7	197
16	2	6	10·3	11·4	103	3	8	6	17·6	19·8	133	15	3	7	10·9	13·3	80
17	2	6	10·3	5·8	122	4	8	6	11·4	14·5	95						
18	2	6	10·7	9·3	325	6	8	6	10·9	8·5	274	0	4	7	37·6	38·3	0
						8	8	6	10·2	12·1	19	1	4	7	16·2	13·4	107
0	3	6	25·9	36·3	90	9	8	6	10·6	12·9	28	3	4	7	30·0	29·8	189
1	3	6	15·0	17·8	307	10	8	6	11·5	12·4	161	4	4	7	14·6	11·4	245
2	3	6	40·2	42·3	231	11	8	6	10·2	10·2	4	7	4	7	14·1	14·5	20
3	3	6	28·4	25·2	69	14	8	6	8·8	7·9	34	8	4	7	32·6	25·4	189
4	3	6	7·5	6·2	62							10	4	7	19·9	17·4	312
5	3	6	38·3	33·6	154	6	9	6	9·8	7·3	216	15	4	7	14·8	20·6	156
6	3	6	29·4	26·5	91	10	9	6	10·1	13·8	78	16	4	7	9·4	10·3	6
7	3	6	29·8	26·7	179												
8	3	6	18·7	15·8	300	2	10	6	9·3	7·7	233	1	5	7	18·4	19·9	121
9	3	6	14·1	14·6	76	4	10	6	9·7	17·3	244	2	5	7	19·0	22·1	113
10	3	6	14·3	10·2	27							3	5	7	11·1	5·3	105
11	3	6	27·9	28·3	323	3	11	6	8·4	12·7	219	4	5	7	26·4	18·4	171
12	3	6	11·9	18·9	307	5	11	6	8·1	12·5	19	6	5	7	38·4	35·5	290
13	3	6	10·1	4·2	27							7	5	7	11·6	12·1	68
15	3	6	10·3	6·9	113							8	5	7	10·3	5·8	114
16	3	6	10·9	11·8	69	2	0	7	8·5	14·8	90	9	5	7	15·8	16·9	261
						4	0	7	38·2	46·7	90	12	5	7	16·6	18·7	29
0	4	6	14·5	5·5	0	5	0	7	7·7	10·1	270						
1	4	6	26·7	27·0	181	6	0	7	7·8	6·3	270	0	6	7	14·8	11·8	180
2	4	6	41·6	37·8	90	7	0	7	61·7	54·7	90	1	6	7	12·1	13·1	145
3	4	6	9·2	10·0	33	8	0	7	18·9	19·5	270	2	6	7	18·9	22·7	284
4	4	6	18·2	14·1	102	9	0	7	9·9	9·2	270	3	6	7	18·7	20·4	122
5	4	6	9·7	12·8	184	11	0	7	22·2	24·5	270	5	6	7	15·0	19·7	254
6	4	6	26·2	23·8	134	12	0	7	11·1	13·1	270	6	6	7	16·5	18·2	208
7	4	6	37·4	34·2	259	13	0	7	11·8	11·3	90	7	6	7	20·5	17·9	326
8	4	6	38·1	34·8	296	14	0	7	21·0	24·5	90	10	6	7	14·4	17·9	63
9	4	6	23·7	22·5	15	16	0	7	10·4	8·9	90	11	6	7	9·8	11·3	339
10	4	6	39·6	35·5	265							13	6	7	12·6	17·5	100
11	4	6	22·0	22·2	89	0	1	7	8·8	17·7	90						
12	4	6	13·1	13·3	99	1	1	7	23·7	32·2	304	1	7	7	14·5	14·3	215
13	4	6	17·8	19·9	253	2	1	7	26·6	32·2	26	4	7	7	16·6	17·5	197
15	4	6	10·3	13·0	61	3	1	7	29·2	29·8	47	7	7	7	14·8	17·3	325
						4	1	7	8·6	8·3	286	11	7	7	16·3	23·6	198
1	5	6	43·9	48·4	25	5	1	7	22·1	23·9	156						
2	5	6	27·1	29·1	169	6	1	7	24·9	13·7	5	2	8	7	13·5	14·0	303
3	5	6	23·9	23·7	189	7	1	7	24·7	21·5	195	7	8	7	14·9	19·7	237
4	5	6	11·3	15·6	18	8	1	7	30·8	22·2	277	11	8	7	9·6	10·9	119
5	5	6	12·2	8·8	18	9	1	7	20·3	14·1	46						
6	5	6	30·0	22·6	267	10	1	7	31·7	32·0	131	2	9	7	15·1	19·5	199
7	5	6	54·1	46·5	159	11	1	7	10·8	8·6	341	5	9	7	13·1	17·3	330
8	5	6	11·7	10·6	198	13	1	7	16·7	15·4	25						
11	5	6	18·7	20·7	21	14	1	7	11·5	6·1	273	2	10	7	10·2	11·7	204
12	5	6	14·2	14·2	134	16	1	7	10·4	11·9	33	6	10	7	9·8	10·3	26

TABLE 4. *Interatomic distances* (Å) *and angles.*

Intramolecular bonded distances

				Average				Average
C(1)–C(2)	1·55	C(1′)–C(2′)	1·56	1·56	C(7)–C(8)	1·54	C(7′)–C(8′)	1·50	1·52
C(2)–C(3)	1·56	C(2′)–C(3′)	1·59	1·57	C(7)–C(9)	1·61	C(7′)–C(9′)	1·55	1·58
C(3)–C(4)	1·54	C(3′)–C(4′)	1·52	1·53	C(7)–C(4)	1·52	C(7′)–C(4′)	1·59	1·56
C(4)–C(5)	1·58	C(4′)–C(5′)	1·55	1·57	C(10)–Br	1·85	C(10′)–Br′	1·89	1·87
C(5)–C(6)	1·55	C(5′)–C(6′)	1·54	1·55	C(2)–Cl	1·81	C(2′)–Cl′	1·75	1·78
C(6)–C(1)	1·59	C(6′)–C(1′)	1·54	1·56	C(2)–N	1·52	C(2′)–N′	1·44	1·48
C(1)–C(10)	1·53	C(1′)–C(10′)	1·51	1·52	N–O	1·16	N′–O′	1·21	1·19
C(1)–C(7)	1·58	C(1′)–C(7′)	1·60	1·59					

XUM

TABLE 4. (*Continued.*)

Intramolecular non-bonded distances

				Average					Average
C(1) · · · C(4)	2·29	C(1′) · · · C(4′)	2·28	2·29	C(4) · · · C(6)	2·45	C(4′) · · · C(6′)	2·34	2·40
C(1) · · · C(8)	2·70	C(1′) · · · C(8′)	2·60	2·65	C(4) · · · C(8)	2·64	C(4′) · · · C(8′)	2·57	2·60
C(1) · · · C(9)	2·68	C(1′) · · · C(9′)	2·65	2·66	C(4) · · · C(9)	2·65	C(4′) · · · C(9′)	2·62	2·64
C(1) · · · C(5)	2·48	C(1′) · · · C(5′)	2·52	2·50	C(5) · · · C(7)	2·37	C(5′) · · · C(7′)	2·47	2·42
C(1) · · · C(3)	2·49	C(1′) · · · C(3′)	2·44	2·47	C(5) · · · C(8)	3·03	C(5′) · · · C(8′)	2·87	2·95
C(1) · · · Br	2·86	C(1′) · · · Br′	2·83	2·85	C(6) · · · C(7)	2·38	C(6′) · · · C(7′)	2·36	2·37
C(1) · · · Cl	2·83	C(1′) · · · Cl′	2·83	2·83	C(6) · · · C(8)	3·04	C(6′) · · · C(8′)	2·80	2·92
C(1) · · · O	3·47	C(1′) · · · O′	3·47	3·47	C(6) · · · C(10)	2·66	C(6′) · · · C(10′)	2·60	2·63
C(2) · · · C(4)	2·38	C(2′) · · · C(4′)	2·45	2·42	C(7) · · · C(10)	2·65	C(7′) · · · C(10′)	2·61	2·63
C(2) · · · C(6)	2·53	C(2′) · · · C(6′)	2·52	2·53	C(8) · · · C(10)	3·30	C(8′) · · · C(10′)	3·18	3·24
C(2) · · · C(7)	2·41	C(2′) · · · C(7′)	2·47	2·44	C(9) · · · C(10)	3·20	C(9′) · · · C(10′)	3·22	3·21
C(2) · · · C(9)	3·05	C(2′) · · · C(9′)	2·99	3·02	N · · · Cl	2·70	N′ · · · Cl′	2·63	2·66
C(2) · · · C(10)	2·59	C(2′) · · · C(10′)	2·59	2·59	N · · · Br	3·42	N′ · · · Br′	3·53	3·48
C(2) · · · Br	3·46	C(2′) · · · Br′	3·37	3·41	O . . . Cl	2·71	O′ · · · Cl′	2·73	2·72
C(3) · · · C(5)	2·62	C(3′) · · · C(5′)	2·55	2·58	O · · · Br	3·77	O′ · · · Br′	3·63	3·70
C(3) · · · C(7)	2·40	C(3′) · · · C(7′)	2·42	2·41	Cl · · · Br	3·82	Cl′ · · · Br′	3·78	3·80
C(3) · · · C(9)	2·99	C(3′) · · · C(9′)	2·92	2·95	Cl · · · C(9)	3·26	Cl′ · · · C(9′)	3·19	3·23
C(3) · · · Cl	2·74	C(3′) · · · Cl′	2·79	2·76	Cl · · · C(7)	3·48	Cl′ · · · C(7′)	3·48	3·48
C(3) · · · O	3·25	C(3′) · · · O′	3·27	3·26					

Intermolecular distances ($\leqslant$4 Å)

C(8) · · · O′	3·48	C(10) · · · Cl′	3·77	C(9′) · · · O_{I}	3·87	C(8′) · · · O_{I}	3·94
C(10′) · · · N_{I}	3·49	C(10′) · · · O_{I}	3·78	C(10′) · · · N'_{V}	3·88	C(9′) · · · N_{I}	3·94
O′ · · · $C(3)_{II}$	3·58	C(5′) · · · Br_{III}	3·80	C(9) · · · O′	3·89	C(8′) · · · $C(3')_{VI}$	3·97
C(4′) · · · O_{III}	3·64	O′ · · · Cl_{II}	3·80	Cl · · · $C(9)_{II}$	3·90	C(6′) · · · O'_{V}	3·99
C(8) · · · Br′	3·65	C(8′) · · · $C(8)_{V}$	3·83	Br′ · · · $C(5')_{V}$	3·92	Cl′ · · · $C(5)_{VII}$	3·99
C(6′) · · · O_{IV}	3·71	C(5′) · · · $C(3)_{IV}$	3·84	C(9) · · · $C(3)_{II}$	3·94	N′ · · · Cl_{II}	4·00
C(8′) · · · O'_{V}	3·74	C(6′) · · · N_{IV}	3·85	C(3′) · · · Cl_{II}	3·94	C(9) · · · $C(4)_{II}$	4·00
C(6′) · · · $C(3)_{IV}$	3·76	C(10) · · · O′	3·85				

The subscripts refer to the following positions:

I	$\frac{1}{2} - x, \quad -y, \frac{1}{2} + z$	V	$-x, y - \frac{1}{2}, \frac{1}{2} - z$
II	$\frac{1}{2} - x, 1 - y, \frac{1}{2} + z$	VI	$-x, y - \frac{1}{2}, 1\frac{1}{2} - z$
III	$x - \frac{1}{2}, \frac{1}{2} - y, 1 - z$	VII	$x, \quad y, 1 + z$
IV	$x - \frac{1}{2}, \frac{1}{2} - y, \quad -z$		

Interbond angles

								Average
C(1)	C(2)	C(3)	107°	C(1′)	C(2′)	C(3′)	102°	104°
C(2)	C(3)	C(4)	100	C(2′)	C(3′)	C(4′)	104	102
C(3)	C(4)	C(5)	114	C(3′)	C(4′)	C(5′)	112	113
C(4)	C(5)	C(6)	103	C(4′)	C(5′)	C(6′)	98	101
C(5)	C(6)	C(1)	104	C(5′)	C(6′)	C(1′)	110	107
C(6)	C(1)	C(2)	108	C(6′)	C(1′)	C(2′)	108	108
C(2)	C(1)	C(7)	100	C(2′)	C(1′)	C(7′)	103	102
C(6)	C(1)	C(7)	97	C(6′)	C(1′)	C(7′)	97	97
C(3)	C(4)	C(7)	103	C(3′)	C(4′)	C(7′)	102	103
C(5)	C(4)	C(7)	100	C(5′)	C(4′)	C(7′)	103	102
C(1)	C(7)	C(8)	120	C(1′)	C(7′)	C(8′)	114	117
C(1)	C(7)	C(9)	114	C(1′)	C(7′)	C(9′)	115	114
C(4)	C(7)	C(8)	119	C(4′)	C(7′)	C(8′)	112	116
C(4)	C(7)	C(9)	116	C(4′)	C(7′)	C(9′)	113	114
C(10)	C(1)	C(2)	115	C(10′)	C(1′)	C(2′)	115	115
C(10)	C(1)	C(6)	118	C(10′)	C(1′)	C(6′)	117	117
C(10)	C(1)	C(7)	117	C(10′)	C(1′)	C(7′)	114	115
C(1)	C(7)	C(4)	95	C(1′)	C(7′)	C(4′)	91	93
C(1)	C(10)	Br	116	C(1′)	C(10′)	Br′	113	114
C(1)	C(2)	N	110	C(1′)	C(2′)	N′	116	113
C(3)	C(2)	N	109	C(3′)	C(2′)	N′	97	103
C(1)	C(2)	Cl	115	C(1′)	C(2′)	Cl′	117	116
C(3)	C(2)	Cl	109	C(3′)	C(2′)	Cl′	113	111
Cl	C(2)	N	108	Cl′	C(2′)	N′	111	109
C(2)	N	O	117	C(2′)	N′	O′	119	118
C(8)	C(7)	C(9)	95	C(8′)	C(7′)	C(9′)	111	103

Experimental.—Copper-K_α radiation, $\lambda = 1{\cdot}542$ Å, was employed in all the measurements. As the crystals are somewhat sensitive to light all experimental work with them was carried out in subdued light. Rotation, oscillation, and moving-film photographs were taken from crystals rotated about the principal zone axes, and these were analysed in the usual way to determine the cell dimensions and systematic halvings, from which the space group was determined uniquely.

The density was determined by flotation in zinc chloride solution.

For the intensity measurements small crystals were employed, completely bathed in a uniform *X*-ray beam. No corrections for absorption were applied. The multiple-film technique [9] with visual estimation was applied to equatorial and equi-inclination upper-layer Weissenberg photographs taken from crystals rotated about the *b* and *c* crystal axes. The usual formulæ for mosaic-type crystals were used to derive values of $|F_o|$. The various layers were put on the same relative scale by comparison of common reflexions on different photographs. The absolute scale was obtained at a later stage by correlation with the final calculated values, $|F_c|$. A total of 1233 independent structure amplitudes was obtained and these are listed in Table 3.

In deriving the calculated $|F|$ values from the atomic co-ordinates theoretical atomic scattering factors were employed: those of Berghuis *et al.*[10] were chosen for carbon, nitrogen, and oxygen, those of Tomiie and Stam [11] for chlorine, and the Thomas–Fermi values [12] for bromine.

The extensive numerical calculations were carried out on the Glasgow University DEUCE computer, with programmes devised by Dr. J. S. Rollett, and we are indebted to the director of the Computing Laboratory, Dr. D. C. Gilles, and his staff for facilities. We are grateful to Dr. Stotherd Mitchell for supplies of crystalline (+)-10-bromo-2-chloro-2-nitrosocamphane and for suggesting the problem to us. The award of a Carnegie Scholarship to G. F. and a Fulbright Scholarship to C. J. F. made possible their participation in this work.

CHEMISTRY DEPARTMENT, THE UNIVERSITY,
GLASGOW, W.2, SCOTLAND. [*Received, October 20th*, 1960.]

[9] Robertson, *J. Sci. Instr.*, 1943, **20**, 175.
[10] Berghuis, Haanappel, Potter, Loopstra, MacGillavry, and Veenendaal, *Acta Cryst.*, 1955, **8**, 478.
[11] Tomiie and Stam, *Acta Cryst.*, 1958, **11**, 126.
[12] "Internationale Tabellen zur Bestimmung von Kristallstrukturen," Borntraeger, Berlin, 1935, Vol. II, p. 572.

---

379. *Magnetic Perturbation of Singlet–Triplet Transitions. Part V.* Mechanism.*

By D. F. EVANS.

Spectrophotometric and solubility measurements on the oxygen–dimethylaniline system show that there is no appreciable formation of complex. The ultraviolet and visible absorption is probably due largely to contact charge transfer. Singlet–triplet absorption spectra perturbed by a paramagnetic metal ion are observed with the manganous complex of 9-anthroylacetone, and, though less clearly, with the corresponding nickel, cobaltous, and ferric complexes. No comparable effect is found with the gadolinium and dysprosium complexes. It is concluded that perturbation of radiative singlet–triplet transitions by oxygen, nitric oxide, and paramagnetic ions is not due to an inhomogeneous magnetic field effect, in agreement with recent theoretical work.

IN previous papers of this series, it was shown that oxygen strongly induces the singlet–triplet absorption spectra of a wide variety of organic molecules (aromatic, heterocyclic, olefinic, and acetylenic). As a method of locating the triplet levels of organic substances,

* Part IV, *J.*, 1960, 1735.

the oxygen perturbation technique, with oxygen under pressure, seems comparable in scope to the well-established phosphorescence technique. This perturbation was attributed to the paramagnetism of the oxygen molecule.[1] It was thought that a spin–orbit perturbation caused by the inhomogeneous magnetic field of the oxygen molecule was possibly involved, although it was also pointed out that charge-transfer interactions might well play some part. In most cases, strong featureless absorption is also observed, which has been assigned as arising from a charge-transfer transition, with the oxygen molecule acting as an acceptor.[1,2,3] Nitric oxide behaves in a similar manner to oxygen.[4]

The present work is concerned with the nature of the interaction between oxygen and the organic substance, and the mechanism of the observed singlet–triplet perturbation.

First, the system dimethylaniline–oxygen was studied quantitatively, both spectrophotometric and solubility measurements being made. Dimethylaniline is known to be an extremely good donor molecule.[5] The observed charge-transfer absorption for oxygen dissolved in dimethylaniline is of comparatively high intensity, and extends well into the visible region.[2] (It completely obscures the expected singlet–triplet bands.)

Secondly, the effect of paramagnetic metal ions on the singlet–triplet absorption spectra of organic molecules has been studied.

Experimental

Apparatus.—Absorption spectra were measured on a Perkin-Elmer 4000 recording spectrophotometer and a Unicam S.P. 500 spectrophotometer. For the oxygen–dimethylaniline system, 1-cm. and 1-mm. quartz cells attached *via* a graded seal to a ground-glass joint and vacuum tap were used. The dissolved atmospheric oxygen was removed by repeated freezing and pumping before the spectrum was measured. After saturation with oxygen at a known pressure the spectrum was again recorded. Finally the oxygen was removed from the solution and a third spectrum measured to ensure that no permanent oxidation had occurred. Corrections were applied to allow for the vapour pressure of the solution, and the change in solubility of the oxygen as the concentration of the dimethylaniline was varied.

Solubility measurements were made on a simple Ostwald-type apparatus. The precision of the results was about $\pm 1\%$.

Materials.—A mixture of dimethylaniline and *ca.* 5% acetic anhydride was fractionally distilled under nitrogen, and the distillate shaken with potassium hydroxide pellets and again fractionally distilled. Approximately 0·005% of ethylenediaminetetra-acetic acid was added to the pure liquid. (Air-saturated) dimethylaniline stabilized in this way remains almost unchanged in ultraviolet absorption for several months if not unduly exposed to light. Presumably the ethylenediaminetetra-acetic acid forms complexes with traces of heavy metals, such as cupric ions, which can act as powerful catalysts for the auto-oxidation of dimethylaniline.

9-Anthroylacetone. A solution of 9-acetylanthracene (35 g.) in ethyl acetate (65 ml.) and anhydrous ether (200 ml.) was quickly added to sodium sand (5·5 g.). When the violent reaction subsided, the mixture was refluxed for 1 hr., cooled, and poured into water (*ca.* 500 ml.). The aqueous layer was acidified with acetic acid, and the crude *9-anthroylacetone* twice recrystallized from ethanol (activated charcoal). The yield was 17 g. (40%) of material, m. p. 136° (Found: C, 82·7; H, 5·2. $C_{18}H_{14}O_2$ requires C, 82·5; H, 5·3%).

The nuclear magnetic resonance spectrum in carbon tetrachloride indicated >95% enolic structure.

Bis-(9-anthroylacetonato)manganese(II). Ammonia (4N; 10 ml.) was slowly added to a solution of " AnalaR " manganese dichloride tetrahydrate (2 g.) and 9-anthroylacetone (5·5 g.) in about 50 ml. of acetone–water (4 : 1), which was vigorously stirred by a stream of nitrogen. The complex was washed with 80% acetone and crystallized from aqueous pyridine

[1] Evans, *J.*, 1957, 1351.
[2] Evans, *J.*, 1953, 345.
[3] Munck and Scott, *Nature*, 1956, **177**, 587.
[4] Evans, *J.*, 1957, 3885.
[5] Orgel, *Quart. Rev.*, 1954, **8**, 422.

to obtain the yellow pyridine *adduct* (*ca.* 50%) [Found: C, 74·1; H, 4·8; Mn, 7·0; N, 5·5. $Mn(C_{18}H_{13}O_2)_2,3C_5H_5N$ requires C, 75·2; H, 5·1; Mn, 6·7; N, 5·2%]. Unlike manganous acetylacetonate, the compound is stable in solution in air.

The magnetic susceptibility χ in pyridine–cyclohexane (95 : 5) was measured by the nuclear magnetic resonance method,[6] and a value of $+25{\cdot}1 \times 10^{-6}$ c.g.s. units at 24° was obtained [based on $Mn(C_{18}H_{13}O_2)_2$]; after correction for the diamagnetic contribution of the ligand, this corresponds to a magnetic moment of 5·96 Bohr magnetons, as compared with 5·92 Bohr magnetons calculated from the spin-only formula for 5 unpaired electrons.

Tris-(9-*anthroylacetonato*)*iron*(III). Pyridine (2 ml.) was added slowly to a well-stirred solution of ferric chloride hexahydrate (1 g.) and 9-anthroylacetone (3 g.) in 70% acetone (*ca.* 40 ml.). The bright red *tris*-(9-*anthroylacetonato*)*iron*(III) was washed with 70% acetone and dried *in vacuo* at 110°. The yield was almost quantitative [Found: C, 76·8; H, 4·8; Fe, 6·8. $Fe(C_{18}H_{13}O_2)_3$ requires C, 77·2; H, 4·7; Fe, 6·65%].

Bis-(9-*anthroylacetonato*)*cobalt*(II). A solution of cobalt acetate tetrahydrate (1 g.) in 70% acetone (*ca.* 10 ml.) was added to a solution of 9-anthroylacetone (3 g.) in 70% acetone (*ca.* 40 ml.). The pink hydrated complex was washed with 70% acetone and heated *in vacuo* at 100° to obtain the green anhydrous *bis*-(9-*anthroylacetonato*)*cobalt*(II) [Found: C, 73·1; H, 5·3; Co, 10·1. $Co(C_{18}H_{13}O_2)_2$ requires C, 74·3; H, 4·5; Co, 10·1%].

Bis-(9-*anthroylacetonato*)*nickel*(II). The yellow-green *bis*-(9-*anthroylacetonato*)*nickel*(II) was prepared in a similar manner to the cobalt compound [Found: Ni, 10·0. $Ni(C_{18}H_{13}O_2)_2$ requires Ni, 10·1%].

Tris-(9-*anthroylacetonato*)*gadolinium*. 9-Anthroylacetone (6 g.) was added to anhydrous alcohol (50 ml.) in which sodium (0·53 g.) had been dissolved. The mixture was warmed for a few minutes and then cooled, and anhydrous gadolinium trichloride (2 g.) added. The solvent was pumped off, and the residue extracted with dry benzene (*ca.* 30 ml.). The yellow *tris*-(9-*anthroylacetonato*)*gadolinium* was precipitated by addition of excess of light petroleum (b. p. 40—60°), washed with light petroleum, and dried *in vacuo* at 110°; it had m. p. *ca.* 240° (decomp.) [Found: C, 67·8; H, 4·4; Gd, 17·5. $Gd(C_{18}H_{13}O_2)_3$ requires C, 68·9; H, 4·2; Gd, 16·7%].

A less pure product was obtained by refluxing freshly precipitated gadolinium hydroxide (1 g.) with a solution of 9-anthroylacetone (3·6 g.) in alcohol (50 ml.). The product was isolated as above.

Tris-(9-*anthroylacetonato*)*dysprosium*. This was prepared in a similar manner to the gadolinium complex and had m. p. *ca.* 250° (decomp.) [Found: Dy, 17·6. $Dy(C_{18}H_{13}O_2)_3$ requires Dy, 17·2%].

Results and Discussion

The dimethylaniline–oxygen system. The absorption spectra of oxygen dissolved in solutions of dimethylaniline in 2,2,4-trimethylpentane were measured. Since oxygen dissolved in pure 2,2,4-trimethylpentane shows no absorption in the wavelength region studied, the simple Benesi–Hildebrand method [7] can be applied directly (Fig. 1). Good straight lines are obtained which pass almost through the origin. This corresponds formally to an equilibrium constant of zero for the assumed dimethylaniline–oxygen complex. The same result is obtained by using the modified procedure due to Scott.[8] The situation is thus analogous to that in the iodine–heptane system,[9] and consequently the absorption shown by oxygen in the presence of dimethylaniline can probably be attributed largely to " contact charge transfer," [10] although it is not possible to exclude the presence of a small concentration of a dimethylaniline–oxygen complex having a large extinction coefficient.

The absorption spectrum of oxygen dissolved in dimethylaniline (Fig. 2) has a pronounced shoulder at *ca.* 380 mμ. The intensity seems much too high for this to be

[6] Evans, *J.*, 1959, 2003.
[7] Benesi and Hildebrand, *J. Amer. Chem. Soc.*, 1949, **71**, 2703; Keefer and Andrews, *J. Amer. Chem. Soc.*, 1952, **74**, 4500.
[8] Scott, *Rec. Trav. chim.*, 1956, **75**, 787.
[9] Evans, *J. Chem. Phys.*, 1955, **23**, 1426.
[10] Orgel and Mulliken, *J. Amer. Chem. Soc.*, 1957, **79**, 4839.

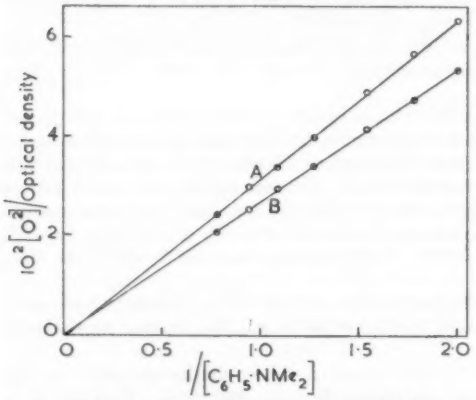
XUM

attributed to an induced singlet–triplet transition. It is more likely that two charge transfer bands are present, corresponding to the two ionization potentials predicted for a substituted benzene compound.[11] Two charge-transfer bands have in fact been observed in several molecular complexes of this type.[12]

An incidental point is that the percentage of oxygen in a gas mixture can be determined by allowing the gas to bubble through an absorption cell containing pure dimethylaniline (stabilized with ethylenediaminetetra-acetic acid) until saturation is obtained. The optical density at any convenient wavelength such as 370 mμ, measured relative to a cell containing deoxygenated dimethylaniline, is accurately proportional to the partial pressure of oxygen in the mixture.

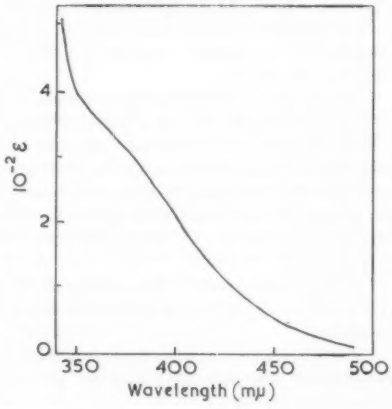
Formation of molecular complexes can also be studied by using solubility measurements.[13] The observed solubility of one component in the other is compared with that

FIG. 1. *Benesi–Hildebrand plots for oxygen–dimethylaniline in 2,2,4-trimethylpentane solution.*



A, $\lambda = 360$ mμ; B, $\lambda = 350$ mμ. *Concentrations are expressed in moles/litre.*

FIG. 2. *Light absorption of oxygen dissolved in pure dimethylaniline.*



expected in the absence of any complex formation. This method is not very accurate because of the difficulty in estimating the latter quantity, but it is free from certain objections attached to the spectrophotometric technique. It has been shown by Jolley and Hildebrand [14] that smooth curves are obtained when the solubilities of oxygen and argon in various (fairly non-polar) solvents are plotted against the solubility parameters of the solvents. The two curves are almost coincident, although the argon solubilities are usually slightly higher (by *ca.* 10%). Accordingly the solubilities of oxygen and argon in dimethylaniline were measured. The values for the Bunsen absorption coefficients at 21° were 0·108 and 0·117, respectively. Since the ratio solubility of argon: solubility of oxygen (1·08 : 1) is very similar to that found for solvents where the extent of complex formation is likely to be much less than with dimethylaniline, these results confirm the absence of any appreciable complex formation between oxygen and dimethylaniline. It is probable that a similar situation exists in the great majority of cases where charge transfer and/or perturbed singlet–triplet bands have been observed in the presence of oxygen. A careful spectrophotometric study of the benzene–oxygen system by Dykgraaf (personal

[11] Orgel, *J. Chem. Phys.*, 1955, **23**, 1352.
[12] McGlynn, *Chem. Rev.*, 1958, **58**, 1113.
[13] Hildebrand, Benesi, and Mower, *J. Amer. Chem. Soc.*, 1950, **72**, 1017.
[14] Jolley and Hildebrand, *J. Amer. Chem. Soc.*, 1958, **80**, 1050.

communication) has given results similar to those described above for the dimethyl aniline–oxygen system.

Perturbation of singlet–triplet absorption spectra by paramagnetic ions. The effect of paramagnetic ions in perturbing (radiative) singlet–triplet transitions has been observed in the phosphorescence spectra of tris(dibenzoylmethyl)gadolinium [15] and porphyrin complexes with paramagnetic transition-metal ions [16] as a shortening of the phosphorescence lifetimes when compared with the lifetimes of related diamagnetic complexes. It should be noted, however, that some care is needed in interpreting phosphorescence lifetimes in the absence of measurements of quantum yield.[17]

FIG. 3.

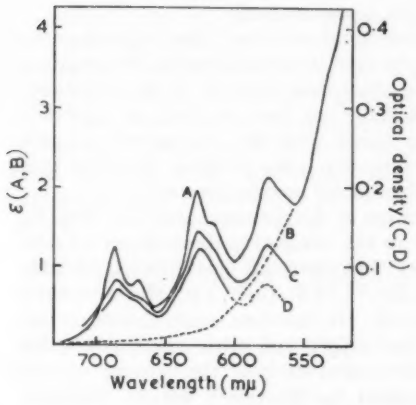


FIG. 4.

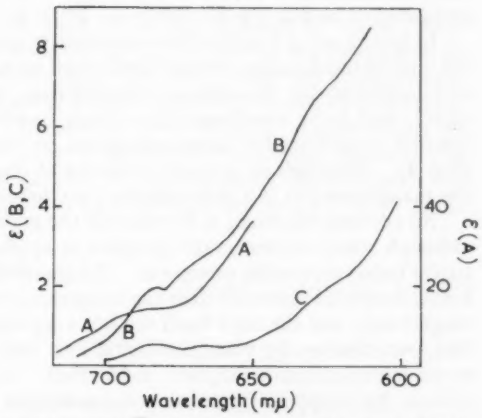


FIG. 3. *Light absorption.* A, *Bis-(9-anthroylacetonato)manganese*(II) (*pyridine solution*); *max.* 14,630, 15,010, 16,010, ca. 16,340 (i), 17,430 *cm.*$^{-1}$. B, *Tris-(9-anthroylacetonato)gadolinium* (*chloroform solution*). C, *Oxygen at* 130 *atm. pressure dissolved in* 0·40M-*solution of* 9-*anthroylacetone* (*in chloroform*; 5·2-*cm. cell*); *max.* 14,620, ca. 15,050(i), 16,000, 17,350 *cm.*$^{-1}$. D, *Oxygen at* 130 *atm. pressure dissolved in* 0·12M-*solution of tris-(9-anthroylacetonato)gadolinium* (*in chloroform*; 5·2-*cm. cell*); *max.* 14,650, ca. 15,040(i), 16,000, ca. 17,350 *cm.*$^{-1}$. *The results for the dysprosium complex were similar to those given for the gadolinium complex.*

FIG. 4. *Light absorption.* A, *Tris-(9-anthroylacetonato)iron*(III) (*chloroform solution*). B, *Bis-(9-anthroylacetonato)nickel*(II) (*pyridine solution*). C, *Bis-(9-anthroylacetonato)cobalt*(II) (*pyridine solution*).

The detection of a similar perturbation in absorption proved rather difficult. It has previously been noted [18] that the results of Chaudhuri and Basu,[19] who claimed to have found the induced singlet–triplet bands of aromatic hydrocarbons such as anthracene and naphthalene in the presence of cupric and ferric acetylacetonates, are almost certainly spurious. It was also found that no singlet–triplet bands could be observed in aqueous, methanolic, or ethanolic solutions of organic substances such as sodium naphthalene-1-sulphonate, 1-methylnaphthalene, quinoline, acridine, phenol, and 9-methylanthracene in the presence of cupric, manganous, nickel, or cobaltous salts, even though the concentrations of the two components were comparable to, or in some cases considerably greater than, those used for oxygen perturbation. In these experiments, the organic molecule presumably cannot approach the paramagnetic ion closely because of the solvation sheath of the ion. Accordingly 9-anthroylacetone was prepared, and complexes of this ligand

[15] Yuster and Weissman, *J. Chem. Phys.*, 1949, **17**, 1182.
[16] Becker and Kasha, *J. Amer. Chem. Soc.*, 1955, **77**, 3669.
[17] Gilmore, Gibson, and McClure, *J. Chem. Phys.*, 1952, **20**, 829.
[18] Evans, *Proc. Roy. Soc.*, 1960, *A*, **255**, 55.
[19] Chaudhuri and Basu, *Trans. Faraday Soc.*, 1958, **54**, 1605.

XUM

with paramagnetic ions were studied. Anthracene and anthracene derivatives give well-defined singlet–triplet absorption bands at comparatively long wavelengths in the presence of oxygen.[1]

Figure 3 shows the spectrum obtained for the manganous complex. The well-defined absorption bands correspond very closely to those observed for the ligand in the presence of oxygen, the only marked difference being that the bands of the complex are appreciably sharper. There can thus be little doubt that they are induced singlet–triplet bands which arise as a result of the perturbing effect of the paramagnetic manganous ion. (The spin-forbidden *d–d* transitions in the visible region normally present in manganous complexes are much weaker, *i.e.*, $\varepsilon < 0{\cdot}1$.[20]) By subtracting the exponential tail of the stronger short-wavelength absorption, the oscillator strength f of the singlet–triplet bands can be estimated to be $2{\cdot}3 \pm 0{\cdot}5 \times 10^{-5}$, *i.e.*, $1{\cdot}2 \times 10^{-5}$ per ligand molecule.

In complexes of 9-anthroylacetone with transition-metal ions other than the manganous ion, any induced singlet–triplet bands tend to be obscured by spin-allowed *d–d* transitions or charge-transfer transitions. Nevertheless, the absorption spectra of the cobaltous, nickel, and ferric complexes show weak bands which from their position are probably induced singlet–triplet bands analogous to those found with the manganous complex (Fig. 4). Although an accurate estimate of their intensity is not possible, it is clear that the manganous ion is a more effective perturber than nickel or cobaltous ions.

No comparable effect is found with the gadolinium or dysprosium complexes (Fig. 3), although when oxygen under pressure is applied to the complexes the induced singlet–triplet bands are readily produced. The gadolinium and dysprosium ions have considerably higher magnetic moments than the manganous ion (Dy^{3+}, 10·5; Gd^{3+}, 7·9; Mn^{2+}, 5·9 Bohr magnetons), and the ionic radii are not very different. It therefore seems almost certain that perturbation by transition-metal ions (and also oxygen and nitric oxide) is not due to an inhomogeneous magnetic field effect. A theoretical study of the benzene–oxygen system by Stephen (personal communication quoted by Murrell[21]) led to the same conclusion.

Very recently, theoretical treatments of the perturbation of singlet–triplet absorption spectra by paramagnetic substances have been given by Hoijtink[22] and by Murrell.[21] These authors considered the states which arise in a complex (or " collision complex ") between the organic substance and the paramagnetic molecule. Hoijtink discussed a mechanism in which a weak electron-exchange interaction is involved, and the intensity of the singlet–triplet transition is " stolen " from singlet–singlet transitions of the organic molecule. Murrell discussed not only this mechanism, but an alternative one in which the intensity is " stolen " from the charge-transfer transition of the " complex." From the experimental results for aromatic molecules perturbed by oxygen, he showed that in these systems the charge-transfer mechanism was almost certainly the more important.

Both mechanisms are consistent with the present results for perturbation by complexed transition-metal ions. The absence of detectable perturbation with complexed rare-earth ions and solvated transition-metal ions can be easily understood in terms of the reduced electron overlap involved. Since a very weak interaction between the organic molecule and the paramagnetic substance can give rise to an appreciable intensity for the perturbed singlet–triplet bands, there is also no inconsistency with the apparent absence of appreciable formation of complexes between oxygen and aromatic molecules.

There is a close correlation between the present results and those of Porter and Windsor[23] and Linschitz and Pekkarinen.[24] These authors studied the effect of paramagnetic substances on the radiationless transitions between the lowest triplet state and the ground

[20] Jørgensen, *Acta Chem. Scand.*, 1957, **11**, 53.
[21] Murrell, *Mol. Phys.*, 1960, **3**, 319.
[22] Hoijtink, *Mol. Phys.*, 1960, **3**, 67.
[23] Porter and Wright, *Discuss. Faraday Soc.*, 1959, **27**, 18.
[24] Linschitz and Pekkarinen, *J. Amer. Chem. Soc.*, 1960, **82**, 2411.

singlet state of aromatic molecules. It was found that oxygen and nitric oxide were much more effective than (solvated) transition-metal ions, while (solvated) rare-earth ions were almost ineffective. A charge-transfer mechanism was suggested by the latter authors. One marked difference, however, is the reduced efficiency of the manganous ion as compared with the other transition-metal ions in perturbing the radiationless transitions. This may, however, be partly due to the fact that only solvated ions were studied.

Finally, it may be noted that the triplet levels of 9-anthroylacetone and of all the metal complexes studied lie at almost the same position (*ca.* 14,600 cm.$^{-1}$). This is not surprising, since there is a shift of only 250 cm.$^{-1}$ from the triplet level of anthracene to that of 9-anthroylacetone.

[*Added in proof.*] A very recent paper by Tsubomura and Mulliken (*J. Amer. Chem. Soc.*, 1960, **82**, 5966) on the ultraviolet absorption spectra caused by the interaction of oxygen with organic molecules seems in general agreement with part of the present work. A minor discrepancy concerns the interpretation of the shoulder in the absorption spectrum of oxygen dissolved in dimethylaniline. Tsubomura and Mulliken attribute this to instrumental error (probably stray light). Since in the present work the shoulder was observed when using 1-mm. cells, where absorption by deoxygenated dimethylaniline is very small in the wavelength region concerned, this interpretation does not seem to be correct.

INORGANIC CHEMISTRY RESEARCH LABORATORIES,
IMPERIAL COLLEGE, LONDON, S.W.7.

[*Received, November 24th*, 1960.]

---

380. *The Preparation and Properties of Chelated Sulphatobis-(ethylenediamine)cobalt*(III) *Salts.*

By C. G. BARRACLOUGH and M. L. TOBE.

The preparation of the bromide and the perchlorate of one of the isomeric $[Co\ en_2SO_4OH_2]^+$ cations is described. The sulphate group occupies one co-ordination position. When heated, these salts lose water and the sulphate group acts as a chelate. The characteristic infrared absorption frequencies of the chelated sulphato-group are reported.

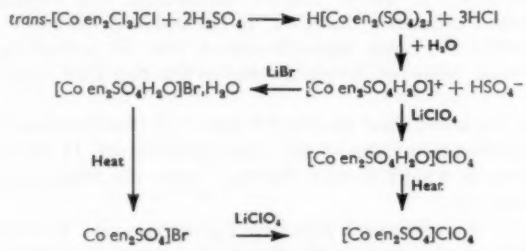
IN a recent paper [1] on the infrared spectra of sulphato-complexes, the characteristic features of the spectra of monodentate and bridging sulphato-groups were described. We have considered the possibility of extending this work to the characterisation of chelated sulphato-groups but have been handicapped by the lack of well-defined complexes of this type. Thus, in Weinland and Sierp's sulphato-complexes [2] only analytical data had been used to support the formulation of the sulphato-group as a chelate. The infrared spectra of these compounds suggest that the sulphato-group is bound in one co-ordination position only, the other being occupied by a water molecule. Duff [3] reported the complex $[Co\ en_2SO_4]Br,H_2O$ but the compound that we obtained on using his procedure appeared to have the structure $[Co\ en_2SO_4H_2O]Br$, the infrared spectrum being characteristic of monodentate sulphate and the compound having a titratable proton. Heating this complex to drive off the water does not result in ring closure.

The chelate complexes $[Co\ en_2SO_4]Br$ and $[Co\ en_2SO_4]ClO_4$ have now been prepared from more accessible reagents, the aquo-complexes, $[Co\ en_2SO_4H_2O]Br$ and

[1] Nakamoto, Fujita, Tanaka, and Kobayashi, *J. Amer. Chem. Soc.*, 1957, **79**, 4904.
[2] Weinland and Sierp, *Z. anorg. Chem.*, 1921, **117**, 59.
[3] Duff, *J.*, 1922, **121**, 450.

XUM

$[Co\ en_2SO_4H_2O]ClO_4$ being characterised as intermediates. These compounds are prepared in accordance with the following scheme:



The anionic nature of the complex ion isolated from the sulphuric acid treatment was demonstrated by passing a freshly prepared solution through a cation-exchange resin in the sodium form. The effluent was highly coloured and freeze-drying yielded a violet

FIG. 1.

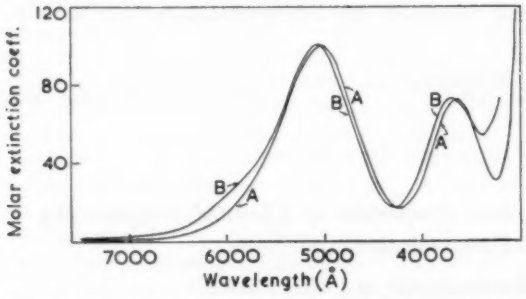


FIG. 2.

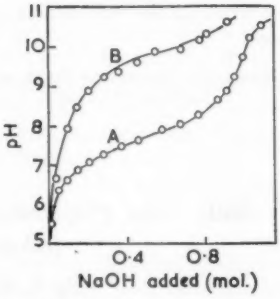


FIG. 1. *The visible absorption spectra of* (A) $[Co\ en_2SO_4H_2O]Br,H_2O$ *(or the analogous perchlorate) and* (B) $[Co\ en_2SO_4]Br$.

FIG. 2. pH *titration curves for the addition of* NaOH *solution to an aqueous solution of* (A) $[Co\ en_2SO_4H_2O]Br,H_2O$ *and* (B) $[Co\ en_2SO_4]Br$ *at* 0°.

powder which was the sodium salt contaminated with large amounts of sodium sulphate. The complex salt was extremely soluble in water and aquated readily, so that we were unable to purify a sample for further examination and characterisation.

When an aqueous solution of this complex was left at room temperature for 24 hr. and then poured into a solution of lithium bromide in acetone a very deliquescent purplish powder was obtained. This powder gave positive tests for ionic bromide and co-ordinated sulphate. The infrared spectrum was consistent with presence of a monodentate sulphate group and was not greatly changed when the material was heated at 110°. The extreme solubility of this complex in water and the ease with which it formed oils discouraged further investigation. When the aqueous solution of the disulphato-complex was saturated with lithium bromide or lithium perchlorate it deposited, in 2—3 days at 0°, purplish-pink crystals of $Co\ en_2SO_4Br,2H_2O$ (I) or $Co\ en_2SO_4ClO_4,H_2O$ (II) respectively. The visible absorption spectra of these two salts are identical and are shown in Fig. 1. A pH titration of the complex with dilute alkali indicates the presence of one co-ordinated water molecule (Fig. 2). The infrared absorption spectrum of the bromide (I) in a Nujol mull (detailed below) is consistent with a monodentate sulphato-complex, the three bands assigned to the sulphato-group and required by the symmetry are: 1130s, 1070s; 978s; 645s, 625m.

Compounds I and II lose all their water at 110—120° and their colours change from pink to purple. The heated products can be recrystallised and have the composition Co en_2SO_4Br (III) and Co $en_2SO_4ClO_4$ (IV). Compound (III) contains ionic bromine * and both have co-ordinated sulphate. The visible absorption spectrum of the bromide differs significantly from that of the aquosulphato-complexes (I) and (II) and is given in Fig. 1. The perchlorate is insoluble in water. The infrared spectrum of the bromide (III) is given below; the maxima assigned to the sulphate group are at 1211s, 1176vs, 1075vs; 993s; 647s, 632s; and 515m cm.$^{-1}$. The number of bands (four) is in agreement with that predicted by Nakamoto *et al.*[1] for a chelated sulphato-group with C_{2v} symmetry. It appears that it is not possible to distinguish between a bridging and a chelated sulphato-group on the basis of the infrared spectrum.

The molecular weight of the bromide corresponds to that expected for a mononuclear complex that splits into two ions, and the conductivity of an aqueous solution is that expected for a 1 : 1 electrolyte (110 ohm cm.$^{-1}$ at 22° for a 0·001M-solution). The pH titration curve for an aqueous solution differs from that of the aquo-sulphato-bromide (I) and indicates that an aquo-group is absent although the complex reacts readily with hydroxide ions.

The visible absorption spectrum of an aqueous solution of bromide (III) changes, with a half-life of 3 hr. at 20°, to that of the aquo-sulphato-complex (I). No free sulphate can be detected in this time. Over much longer periods the spectrum changes towards that of *cis*-[Co $en_2(H_2O)_2$]$^{3+}$ and free sulphate ions can then be detected in the solution. Semiquantitative measurements indicate that the opening of the chelate ring is about twenty times faster than the subsequent loss of the sulphate.

Experimental

Aquosulphatobis(ethylenediamine)cobalt(III) *Bromide.*—*trans*-Dichlorobis(ethylenediamine)-cobalt(III) chloride (10 g.) was added to concentrated sulphuric acid (20 ml.) in a beaker and, when the initial effervescence had subsided, the mixture was gently warmed. The complex slowly dissolved, evolving hydrogen chloride and forming a violet solution. The temperature was raised to 120° until the gas evolution had ceased and the oil was then allowed to cool and poured into alcohol (1 l.) which was continuously stirred to prevent the formation of an oil. The solid was filtered off, washed with alcohol and ether, and dried in a vacuum. The deliquescent solid was dissolved in water (20 ml.), treated with lithium bromide (5 g., anhydrous) in water (5 ml.), and set aside at 0°. After 3 days the purple crystals of the *bromide* were filtered off, washed with alcohol and ether, and air-dried (yield, 1·6 g.) [Found: Br, 20·1; SO_4, 24·7; H_2O, 9·6. $Co(C_2H_8N_2)_2SO_4Br,2H_2O$ requires Br, 20·5; SO_4, 24·5; H_2O, 9·6%]. A second crop (1·8 g.) was obtained after a further 3 days. When the mother-liquor was kept too long the bromine entered the co-ordination sphere and crystals of *cis*- and *trans*-[Co en_2Br_2]Br were deposited.

Infrared maxima were at 1282s, 1208w, 1147sh, 1130s, 1099m, 1070s, 1052s, 1000m, 978s, 893w, 881w, 800sh, 794s, 645s, 625m, 595sh, 585s.

Aquosulphatobis(ethylenediamine)cobalt(III) *perchlorate* was made by an analogous method, hydrated lithium perchlorate (10 g.) being added to the solution (yield, 7 g.). It is less soluble in water than the bromide [Found: H_2O, 5·4. $Co(C_2H_8N_2)_2SO_4ClO_4,H_2O$ requires H_2O, 4·6%].

Sulphatobis(ethylenediamine)cobalt(III) *Bromide.*—A powdered specimen of the aquosulphato-bromide was heated at 110° for 24 hr. in an electric oven and lost weight equivalent to two water molecules per cobalt atom. The *product* was recrystallised by dissolving it in the minimum amount of cold water and adding solid sodium bromide, then forming short purple-red needles [Found: SO_4, 27·2; Br, 21·9. $Co(C_2H_8N_2)_2SO_4Br$ requires SO_4, 27·0; Br, 22·5%]. The apparent molecular weight was determined by measuring the freezing-point depression [4] of a 0·015M-aqueous solution (Found: *M*, 187. [Co en_2SO_4]$^+Br^-$ requires *M*, 177). Since the

* The complex [Co en_2SO_4Br] can be prepared by heating the salt *cis*-[Co $en_2H_2OBr]SO_4$. This does not initially give a positive reaction for ionic bromide.

[4] Cf. Richards, *Z. phys. Chem.*, 1903, **44**, 563.

activity coefficients of these ionic species may be well removed from unity at these concentrations the method was calibrated by means of 0·015M-potassium bromide (Found: *M*, 67. Calc. for K^+Br^-: *M*, 59).

Infrared maxima were at **3229s, 3175m, 3151m, 3037s, 2943m, 2884m, 1590sh, 1570s, 1451s, 1391w, 1370w, 1323sh, 1314w, 1299sh, 1282sh, 1277m, 1224sh, 1211s, 1176vs, 1136m, 1111w, 1088sh, 1075vs, 1053s, 993s, 948w, 936w, 910w, 903w, 893w, 879w, 827m, 806s, 667m, 647s, 632s, 585s, 573w, 515m, 505w, 480w** cm.$^{-1}$ (Nujol and hexachlorobutadiene mulls).

Sulphatobis(ethylenediamine)cobalt(III) *perchlorate* can be made by heating the aquosulphatoperchlorate. It is insoluble in water and cannot be recrystallised without decomposition. A better crystalline specimen was obtained by carefully adding lithium perchlorate solution to a saturated aqueous solution of the bromide. Short purple-red needle crystals were obtained [Found: SO_4, 26·0. $Co(C_2H_8N_2)_2SO_4.ClO_4$ requires SO_4, 25·6%].

One of us (C. G. B.) acknowledges the award of a travelling scholarship from the University of Melbourne.

William Ramsay and Ralph Forster Laboratories,
University College,
Gower Street, London, W.C.1.

[*Received, November 4th*, 1960.]

---

381. *Basic Tin*(II) *Nitrate.*

By J. D. Donaldson and W. Moser.

Of the various tin(II) nitrates reported in the literature, the only one preparable in a pure state from aqueous solution is found to be a basic nitrate $Sn_3(OH)_4(NO_3)_2$. The difficulties inherent in work with tin(II) nitrates are discussed, and the preparation and analysis of the basic nitrate described. The substance is a high-explosive; full tests of its explosive characteristics are listed.

The thermal decomposition, at 125°, has been studied in detail. The main products are found to be tin(IV) oxide, nitric oxide, and water, in agreement with the suggested formula. *X*-Ray diffraction data show that the crystals are monoclinic with unit-cell dimensions $a = 16{\cdot}16$ Å, $b = 9{\cdot}07$ Å, $c = 16{\cdot}38$ Å, $\beta = 122°$, and 8 formula units per cell.

An explosive tin(II) nitrate was investigated by Weber [1] who obtained it by slow addition of sodium carbonate to a freshly prepared solution of tin(II) oxide in nitric acid. The white crystalline product was partly decomposed by water, oxidised slowly in air, and exploded when rubbed, struck, or heated above 100°. Weber considered it to be anhydrous and gave it the formula $Sn_2O(NO_3)_2$. Bury and Partington [2] were unable to prepare a truly explosive solid. The only other mention of a similar material is in a report of the Government Chemist [3] in which an explosion in a flour mill was attributed to the formation of basic tin(II) nitrate.

Dilute solutions of tin(II) nitrate are reasonably stable. They may be prepared either by metathesis from the chloride or sulphate, or by dissolution of tin(II) oxide, hydrous or anhydrous, in dilute nitric acid. Attempts to evaporate to crystallisation result in decomposition, which may occasionally be violent. The decomposition produces tin(IV) oxide and various nitrogen compounds, principally hydroxylamine and nitrous oxide.[4,5] From the equations for the various possible nitrate electrodes, the oxidation potential of the nitrate ion is strongly dependent on pH; the nitrate ion is a more powerful oxidant in strongly acid than in weakly acid or neutral solution. It follows that preparation of a

[1] Weber, *J. prakt. Chem.*, 1882, **26**, 121.
[2] Bury and Partington, *J.*, 1922, **121**, 1998.
[3] Report of the Government Chemist, 1922—1923.
[4] Milligan and Gillette, *J. Phys. Chem.*, 1924, **28**, 747.
[5] Montemartini and Vernazza, *Ind. Chim.* (*Italy*), 1931, **6**, 632.

normal nitrate would be even more difficult than that of the basic nitrate, especially as Tobias [6] has shown that tin(II)–hydroxo-cation complexes persist to as low a pH as 1·5.

Experimental

We find that a satisfactory yield of the moderately soluble crystals can be obtained only by starting from fairly concentrated nitric acid and hydrous tin(II) oxide.[7] To avoid decomposition, the first portions of hydrous oxide must be added very slowly to the cooled acid. After saturation, amounting also to partial neutralisation, the temperature can be raised slightly without decomposition, the acid saturated with further hydrous oxide, and the process continued in stages to a boiling saturated solution. This stepwise procedure is essential for the preparation of a pure product in good yield.

Preparation.—Copper(II) sulphate (50 g.) of analytical-reagent grade was dissolved in water (400 ml.) and sulphuric acid (20 ml.), and boiled with metallic tin (50 g.), also of analytical-reagent grade, until the solution became colourless and the deposited copper was covered with a grey coating of tin. The resulting solution of tin(II) sulphate [8] was filtered, kept under an atmosphere of carbon dioxide, and treated with a 1 : 1 v/v ammonia (*d* 0·88)–water solution (280 ml.) to precipitate hydrous tin(II) oxide.[7] The precipitate was washed by centrifuging it with air-free distilled water until quite free from ammonia. It was suspended in a little air-free distilled water, filtered by suction (Whatman no. 5 paper), and partly dried by pressure on the filter. Two batches of this partly dried paste are required for the remaining stages but are best prepared separately because of difficulties with washing and drying of bigger batches.

Nitric acid (26 ml.; *d* 1·42) of analytical-reagent grade and water (39 ml.) were cooled to approx. −20° in ice–salt. Hydrous tin(II) oxide paste was added gradually in very small portions and with stirring until the acid was saturated. The temperature was allowed to rise to 0°, the acid saturated with more hydrous oxide, and the process continued in further stages of about 20° each to a boiling saturated suspension. The suspension was boiled for about 2 min., filtered by suction into a warm flask, and allowed to cool slowly. The crystalline product was filtered off, washed rapidly with acetone (without prior washing with water!), and dried successively by suction and *in vacuo* over silica gel and paraffin wax (yield, 18—25 g.). The pH of the mother-liquor was about 1·5.

A less pure product, in poorer yield, can be obtained by the simpler procedure of treating the double batch of hydrous oxide with the minimum of 2 : 3 v/v nitric acid–water required to dissolve it at −20° and adding solid sodium hydrogen carbonate in small amounts until a permanent precipitate is obtained. The suspension can then be boiled, filtered, and cooled, and the crystalline product treated as in the first method.

General Properties.—Basic tin(II) nitrate is crystalline, slightly soluble in cold, more soluble in hot water, but partly decomposed by either to hydrous tin(II) oxide. Careful control of the hydrolysis results in the production of crystalline hydrous tin(II) oxide.[9] Basic tin(II) nitrate decomposes explosively at 125°. On storage, the crystals are stable for a few months in a glass container, but eventually become yellow and finally decompose spontaneously with slight explosion to give tin(IV) oxide.

When a concentrated solution of basic tin(II) nitrate in 2N-hydrochloric acid, or a similar solution prepared by metathesis from tin(II) chloride and lead nitrate, is kept for a few days, a gelatinous material is deposited. The rather diffuse *X*-ray powder pattern of the dried material, typical of a vitreous solid, is essentially that of tin(IV) oxide. When this material is heated, water and oxides of nitrogen are given off. The material must therefore be regarded as a hydrated tin(IV) oxide with sorbed nitric acid or nitrate inclusions, and previous [10,11] reports of it as a tin(IV) nitrate are, in our opinion, erroneous.

Analysis.—Tin(II) and total tin were determined by the method of Donaldson and Moser,[12] except that in the tin(II) determination the sample was simultaneously dissolved and oxidised by a single injection of iron(III) chloride solution. Nitrate was determined by reduction with

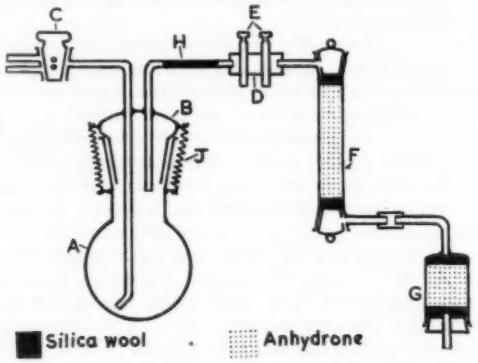
[6] Tobias, *Acta Chem. Scand.*, 1958, **12**, 198.
[7] Donaldson and Moser, *J.*, 1961, 835.
[8] Donaldson and Moser, *J.*, 1960, 4000.
[9] Donaldson, *Acta Cryst.*, 1961, **14**, 65.
[10] Ditte, *Ann. Chim. Phys.*, 1882, **27**, 159.
[11] Walker, *J.*, 1893, **63**, 845.
[12] Donaldson and Moser, *Analyst*, 1959, **84**, 10.

XUM

Devarda's alloy and estimation as ammonia. The substance was found to contain water (contrary to Weber's finding [1]) and a special apparatus was devised for its determination because of the explosive nature of the material.

The apparatus (see Figure) consisted of a 50 ml. explosion vessel (A) fitted with a cap (B) through which passed two tubes. One led through a two-way tap (C) to a vacuum pump or to a supply of dry oxygen; the other tube was packed with silica wool (H) and terminated in a piece of aged rubber tubing (D), closed during the explosion by two spring clips (E). An absorption tube (F) and a guard-tube (G) were attached for the water determination. A tap at (E) was

Apparatus for water analysis.



found unsatisfactory because grease volatilised into the absorption tube. The B 19 ground-glass joint was held in place by two springs (J). In each determination about 0·15 g. of sample was weighed into the explosion vessel, the vessel evacuated, and the sample exploded by heat. The vessel was then swept out with dry oxygen and the water determined.

The results of triplicate analyses on two typical samples were:

	Sample 1	Sample 2	Required for $Sn(NO_3)_2,2SnO,2H_2O$
Tin(II)	64·7, 64·9, 64·5	64·8, 64·8, 64·9	64·9
Tin (total)	65·1, 65·1, 65·1	64·8, 65·1, 65·1	
Nitrate	22·3, 22·3, 22·4	22·1, 22·1, 22·2	22·1
Water	6·3, 6·6, 6·7	6·7, 6·8, 6·8	6·6

Thermal Decomposition.—The thermal stability of basic tin(II) nitrate was tested in an m. p. apparatus. The purest samples exploded at 125°, all others between 120° and 125°.

The decomposition products were studied by exploding samples in a vessel similar to that illustrated, but attached through a tap at (E) to a grid consisting of a liquid-air trap, a manometer, and a gas cell. The solid residue was found, by *X*-ray diffraction powder examination and by constancy of weight on ignition,[7] to be tin(IV) oxide. The gaseous products were water (see analysis above) and oxides of nitrogen. The dried gases were examined by infrared spectroscopy [13] and found to contain 93% or more of nitric oxide, approximately 3% of nitrogen dioxide, and ½% of nitrous oxide. A small amount of gas was not condensed in the liquid-air trap, and can be accounted for as nitrogen.

Explosive Characteristics.—Ignition of samples by friction, impact, spark, and heat was examined by standard tests, as was the explosive power. The results are quoted, in the same order, as length of a pendulum initiating the friction, weight and fall-height of a hammer, energy of a spark from a condenser discharge, temperature of a Wood's metal bath, and expansion of a lead block.

	Friction (cm.)	Impact (oz./inch)	Spark (% ignitions at erg)	Heat (° c)	Power (c.c./g.)
Basic tin(II) nitrate	72—82	45—75	None at $1·25 \times 10^6$	150—152	6
Lead azide	0·6—2·7	120	50% at 400—18,000	315	10
Lead styphnate		140	50% at 500	250—255	15

[13] Nightingale, *et al.*, *J. Phys. Chem.*, 1954, **58**, 1047.

The ignition temperatures recorded in the standard test are higher than those found in an m. p. apparatus, because in the former test the sample is heated rapidly and required to ignite in less than 5 sec., whereas in the latter the sample and surroundings are at nearly the same temperature.

Crystallography.—Basic tin(II) nitrate consists of snow-white acicular crystals which show parallel extinction and have $n > 1{\cdot}74$, negative elongation, and high birefringence. *X*-Ray data show that the crystals are monoclinic with long axis *b* and cleavage (100).

Crystal data: $Sn_3(OH)_4(NO_3)_2$. $M = 548{\cdot}1$. Monoclinic $a = 16{\cdot}16 \pm 0{\cdot}02$, $b = 9{\cdot}07 \pm 0{\cdot}02$, $c = 16{\cdot}38 \pm 0{\cdot}02$ Å, $\beta = 122°$, $U = 2036$ Å^3, $D_m = 3{\cdot}61 \pm 0{\cdot}02$ g./c.c. (by suspension in a mutual solution [14] of thallous formate and thallous malonate in water). $Z = 8$. $D_c = 3{\cdot}64$ g./c.c. Filtered Cu-K_α radiation; single-crystal rotation photographs about all three axes, and Weissenberg and oscillation photographs about *b*.

There is strong pseudo-halving of both *a* and *c*, giving a pseudo-unit-cell with dimensions $a = 8{\cdot}08$, $b = 9{\cdot}07$, $c = 8{\cdot}19$ Å, $\beta = 122°$. The weak superlattice reflections were detected in the rotation photographs about *a* and *c*. The Table contains the *X*-ray diffraction powder data obtained by using 11·64 cm. cameras with filtered Cu-K_α radiation. The spacings longer than 2·8 Å have been indexed.

TABLE 1. *X-Ray diffraction powder data for basic tin(II) nitrate.*

d (Å)	Rel. intensity	Index of reflection	Calc. *d* spacings	*d* (Å)	Rel. intensity	*d* (Å)	Rel. intensity
7·03	m	002	7·12	2·79	m	1·996	vw
6·78	ms	200	6·85	2·69	w	1·982	vw
5·55	vw	$\bar{2}12$	5·57	2·60	vvw	1·880	w
5·52	vw	012	5·55	2·56	vvw	1·822	vw
4·58	s	020	4·55	2·53	vvw	1·789	vvw
4·33	w	$\bar{2}04$	4·28	2·26	m	1·738	vvw
3·79	s	014	3·78	2·23	vw	1·710	vvw
3·49	w	004	3·47			1·591	vw
3·41	w	400	3·43			1·507	vw
3·30	w	$\bar{4}14$	3·33			1·397	vvw
3·18	vs	410	3·18				
2·98	vw	222	2·98				
2·89	vvw	$\bar{4}14$	2·89				

DISCUSSION

The analytical results agree with a formula $Sn(NO_3)_2,2SnO,2H_2O$. A basic tin(II) nitrate of this formula would, in a stoicheiometric reaction, be expected to break down to $3SnO_2$, $2H_2O$, and $2NO$, in complete agreement with the results of the thermal decomposition studies. Moreover, the unit-cell dimensions, the measured density, and the suggested formula weight together give the calculated value of Z as 8·01. Lattice considerations require Z to be an integer, so that the calculated value's proximity to a whole number may be taken as a further indication of the correctness of the formula.

However, since oxide ions cannot co-exist in a solid structure with free water, the water must be present as hydroxyl, and the most satisfactory formula must be tritin(II) tetrahydroxide dinitrate $Sn_3(OH)_4(NO_3)_2$. This formulation would be in agreement with the work of Tobias [6] who has shown that $Sn_3(OH)_4^{2+}$ is the main species formed in the hydrolysis of tin(II) solutions.

The co-existence in the substance of tin(II) and nitrate is responsible for the explosive properties and for many difficulties encountered in all stages of the work. Attempts to prepare a normal nitrate are still in progress. At the low pH needed to suppress hydrolysis, only dilute solutions are stable. Freezing of these solutions has so far produced only ice, alone or in admixture with a possible normal nitrate. A eutectic mixture of this kind would account for the dubious $Sn(NO_3)_2,20H_2O$ reported by Weber.[1]

Comparison with the standard initiating explosives lead azide and lead styphnate shows basic tin(II) nitrate to be more sensitive to impact and heat, but less sensitive to friction than either. The only remarkable feature is its very high resistance to spark

[14] Clerici, *Rend. Accad. Lincei*, 1907, **16**, 187; 1922, **31**, 116.

XUM

ignition, not a single ignition having been recorded in 50 discharges at maximum spark energy. The power, as measured by the lead-block test, is less than that of the standard explosives, the most likely reason being that only 18% of the solid is converted into gaseous products in the explosion. In the circumstances, basic tin(II) nitrate seems unlikely to have commercial uses, unless its high spark-resistance or low detonation temperature should suit some specialised application.

We are grateful to Imperial Chemical Industries Limited, Nobel Division, for conducting the explosive tests, to Dr. D. C. McKean and Dr. H. F. W. Taylor for helpful discussion, and to D.S.I.R. for a research grant (to J. D. D.).

UNIVERSITY OF ABERDEEN, CHEMISTRY DEPARTMENT,
OLD ABERDEEN, SCOTLAND. [*Received, November 14th*, 1960.]

---

382. *Ruthenium Red.*

By J. M. FLETCHER, B. F. GREENFIELD, C. J. HARDY, D. SCARGILL, and J. L. WOODHEAD.

Experiments have shown * that the ruthenium red cation is $[Ru_3O_2(NH_3)_{14}]^{6+}$ in which there are two oxo-bridges and the average oxidation number of ruthenium is +10/3. The cation is oxidised reversibly by a one-electron change to the more paramagnetic brown cation $[Ru_3O_2(NH_3)_{14}]^{7+}$. The relation to other polynuclear complexes is discussed.

JOLY [1] formulated ruthenium red as $Ru_2Cl_4(OH)_2,7NH_3,3H_2O$, and Morgan and Burstall,[2] who prepared from it supposed mononuclear complexes of ruthenium, as $[Ru^{III}(OH)Cl(NH_3)_4]Cl,H_2O$. The latter structure was rejected by Gleu and Breuel [3] because $[Ru^{III}(OH)Cl(NH_3)_4]^+$ is paramagnetic whereas ruthenium red is diamagnetic. It has been suggested that the highly coloured cation is polynuclear, but further evidence on its structure has not been advanced.

Our interest in ruthenium red arose from a view that the diamagnetism and intense colour of many complexes of ruthenium are due to their being polynuclear. In particular, the occurrence in solution of an aquochloro- [4] and an aquonitrato-complex [5,6] as transient violet species with unusually high molar extinction coefficients ($\varepsilon_{Ru} \sim 20{,}000$ at $\lambda_{max.}$ ~550 mμ) suggested a chromatic group similar to that in ruthenium red for which we find that ε_{Ru} is 21,000 at $\lambda_{max.}$ 532 mμ. It has now been shown that this cation, here called ruthenium red, has no complexed halogen groups, and behaves as a trinuclear complex in which, associated with three ruthenium atoms, there are 14 nitrogen atoms which can be liberated as ammonia. This suggests that the red cation has two oxo-bridges, as in (I), to satisfy hexa-co-ordination of the ruthenium atoms. This cation is oxidised, reversibly,

$[(NH_3)_5Ru{-}O{-}Ru(NH_3)_4{-}O{-}Ru(NH_3)_5]^{6+}$ (I) Red

$[(NH_3)_5Ru{-}O{-}Ru(NH_3)_4{-}O{-}Ru(NH_3)_5]^{7+}$ (II) Brown

in acid solution to a brown cation (II). The average oxidation state of ruthenium atoms in the respective cations are 10/3 and 11/3. The approach to diamagnetism shown by the red cation points to a linear configuration of the Ru–O–Ru–O–Ru group.

* The main conclusions from this work were given in April 1959 to the International Conference on Co-ordination Chemistry, London (*Chem. Soc. Spec. Publ.* No. 13, p. 136, and U.K.A.E.A. Document AERE–R2877, 1959).

[1] Joly, *Compt. rend.*, 1892, **115**, 1299.
[2] Morgan and Burstall, *J.*, 1936, 41.
[3] Gleu and Breuel, *Z. anorg. Chem.*, 1938, **237**, 350.
[4] Wehner and Hindman, *J. Phys. Chem.*, 1952, **56**, 10.
[5] Fletcher, Jenkins, Lever, Martin, Powell, and Todd, *J. Inorg. Nuclear Chem.*, 1955, **1**, 378.
[6] Woodhead, unpublished results; Fletcher, *J. Inorg. Nuclear Chem.*, 1958, **8**, 277.

Experimental and Results

Preparations.—Ruthenium red chloride. Joly,[1] and Morgan and Burstall,[2] prepared their red compound from reactive anhydrous ruthenium trichloride made at 360—400° from the metal, chlorine, and a little carbon monoxide. An industrial method is to age aqueous commercial ruthenium chloride, largely polynuclear aquochloro-complexes [6] of Ru^{IV}, in an excess of ammonia for several days. Our experiments indicate that it is formed slowly when $[Ru^{III}(NH_3)_6]Cl_3$ in aqueous ammonia is exposed to air, it being immaterial how the hexammine solution is made. Greater concentration of hexammine increases the yield and, as Joly found, allows the red to be crystallised when the aged and warm solution is cooled; it also makes the ethyl alcohol precipitation used by Morgan and Burstall unnecessary, thereby giving a better separation from the more soluble by-products of ageing.

Commercial ruthenium trichloride (5 g.; Ru 38%), tested by infrared spectroscopy for freedom from nitrosylruthenium (an impurity found in several batches), in 0·25N-hydrochloric acid (25 ml.) was reduced to Ru^{III} by 2 hours' refluxing with ethyl alcohol (5 ml.). The liquid was evaporated to 5 ml. (~4M-Ru) and ammonia (*d* 0·880; 20 ml.) was added. Ruthenium red was formed when the solution, at *ca.* 90°, was exposed to air for 2—3 hr. with frequent additions of ammonia. To the 10 ml. of liquor with its crystalline deposit, 10 ml. of water were added; the mixture was heated to 80° and centrifuged whilst hot. The supernatant liquid, cooled to 0°, gave on centrifugation 1·1 g. of solid (ε_{Ru} 9100 at 532 mμ in H_2O). Further evaporation of the mother-liquor with more ammonia, produced two additional crops of 1·06 g. and 1·03 g. with ε_{Ru} 11,800 and 1380 respectively at 532 mμ. Solutions of the three fractions showed a peak at 725 mμ, particularly marked in the first, relating to an unidentified complex. Each fraction was recrystallised by digesting it with 0·5N-ammonia (10 ml.) at 60°, centrifuging the mixture whilst hot, and cooling the supernatant liquid to 0°. The three crops were washed with ice-cold water, ethyl alcohol, and diethyl ether; after drying in air at room temperature, they weighed 0·25, 0·28, and 0·08 g. respectively (yield 11·5%). They were similar spectrophotometrically, with $\lambda_{max.}$ 532 mμ (ε_{Ru} 20,500 ± 2% in water), and in ruthenium content (range, 0·7%). In another preparation ($\lambda_{max.}$ 532 mμ; ε_{Ru} 21,400 in H_2O) of the *salt*, a 20% yield was attained and the three crops were combined before recrystallisation {Found: Ru, by Woodhead's method,[7] 35·7, 35·1; N, by distillation with Devarda's alloy, 22·1, 22·4; Cl, by Volhard's method after decomposition by boiling with 2N-KOH, 24·4, 24·2; H_2O, by Karl Fischer's method, 8·1. $[Ru_2O_2(NH_3)_{14}]Cl_6,4H_2O$ requires Ru, 35·3; N, 22·8; Cl, 24·8; H_2O, 8·4%}. The solubility of the salt in 0·1N-ammonia at 0° was 36 g./l. When heated to constant weight at 85°, it lost 4·2%, corresponding to the formation of the dihydrate. Another preparation, heated at 110°, lost 6·8, 8·3, 8·9% after 1, 2, and 3 hr., respectively, but there was no loss of nitrogen: the spectrum of the residue showed that about 10% of the red cation had been oxidised to the brown cation, and as the complex aged in air its weight increase (3·7%) corresponded to the formation of the dihydrate.

Ruthenium brown nitrate. Commercial ruthenium red (1·5 g. as chloride), in aqueous ammonia (pH 10; 100 ml.), was freed from impurities, *e.g.*, nitrosylruthenium complexes, and from chloride by two preliminary precipitations of this relatively insoluble (0·34 g./l. in water at 25°) nitrate from hot, dilute nitric acid. The precipitates were dissolved, with auto-reduction to the red cation, in ammonia at pH 10. The purified *salt* was then reprecipitated from hot 0·2N-nitric acid, washed with 0·01N-nitric acid, ethyl alcohol, and ether, and dried at room temperature (yield 0·4 g., 31%). The spectrum (Fig. 1), $\lambda_{max.}$ 460 mμ (ε_{Ru} 14,100) in 0·01N-nitric acid, did not change after yet a further reprecipitation {Found: Ru, 28·0; total N, by Devarda's alloy, 26·7; Cl, <0·1. $[Ru_2O_2(NH_3)_{14}](NO_3)_7,5H_2O$ requires Ru, 27·6; N, 26·8%}.

When the salt was boiled in 2M-sodium hydroxide in the absence of Devarda's alloy, the nitrogen liberated as ammonia after 3 hr. was only 15·4% (calc. N as NH_3, 17·8%). Failure to release all the nitrogen as ammonia is attributed to the formation of very stable amido-complexes of Ru^{VI} (see below).

Ruthenium brown sulphate. To ruthenium red (0·77 g.) in 0·25N-sulphuric acid (50 ml.) was added 0·05N-ceric sulphate until the red colour was discharged (19 ml.). The precipitate formed was centrifuged off, washed with 0·01N-sulphuric acid until free from red colour, then with alcohol and ether, and dried at room temperature (yield 79%). The *salt* was light brown {Found: Ru, 29·4; N, 18·6; SO_4, 31·0; H_2O, by Karl Fischer's method, 12·8; Cl, 0·8.

[7] Woodhead, U.K.A.E.A. Document, A.E.R.E.—R-3279, 1960.

XUM

$[Ru_2O_2(NH_3)_{14}]_2(SO_4)_7,15H_2O$ requires Ru, 29·1; N, 18·8; SO_4, 31·9; H_2O, 12·9%}. The loss, 8·8%, on heating to constant weight at 85° corresponds to the formation of the tetrahydrate. Thermogravimetric analysis showed no further loss in weight up to 170° but after heating to 200° the infrared spectrum indicated slight decomposition. The salt was too insoluble (0·02 g./l. in 0·01N-sulphuric acid at 25°) for a reliable absorption spectrum to be obtained. It dissolved rapidly in aqueous ammonia or alkali in which it gave a solution of ruthenium red with $\lambda_{max.}$ 532 mμ (ε_{Ru} 21,000).

Properties of Solids.—Infrared spectra. The red (as chloride) and the brown (as nitrate and sulphate) were examined (see Table) as mulls in Nujol and hexachlorobutadiene in the 2—15 μ region with a Hilger H800 double-beam spectrometer, the specimens being first dried to constant weight at 85°. The mulls were mounted as thin films between rock-salt windows. For deuteration (~90%), the red chloride was dissolved in D_2O and dried under a vacuum at room temperature. The red complex differs from the brown complex in two respects. First, the band at 3477 cm.$^{-1}$, assigned to the stretching vibration of H_2O in the red chloride is shifted to 3361 cm.$^{-1}$ in the brown nitrate and to 3380 cm.$^{-1}$ in the brown sulphate. Secondly, the ammine symmetric deformation and rocking bands in the red complex have shoulders on the low-frequency side which are shown to be separate bands by deuteration: the ratio, 1 : 2·5, of the absorption densities of the symmetric deformation bands in the deuterated form suggests that four of the fourteen ammine ligands in the complex are different from the other ten. Bands

Infrared absorption frequencies (cm.$^{-1}$).

Red chloride	Brown nitrate	Brown sulphate	Assignment	Group
3477 (2594) m	3361 sh	3380 sh	O–H (O–D) stretch	H_2O (D_2O)
3422 (2542) sh				
3237 (2415) s	3200 s	3197 s	N–H (N–D) stretch	NH_3 (ND_3)
3131 (2279) s	3096 s	3164s		
1614 (1183) s,b	1615	1630 s,b	Degenerate deformation	NH_3 (ND_3) and H_2O (D_2O)
(1155) sh				
1295 sh (1056) m	*		Symmetric deformation	NH_3 (ND_3)
1276 (976) s	*	1336 s		
842 sh		856 m,b	Rocking	NH_3
817 m,b	*			

Data for deuterated samples are in parentheses. * Obscured by nitrate-ion absorptions.

due to nitrate and sulphate ions, with none due to nitrato- or sulphato-groups, were present respectively in the spectra of the two brown salts. There were no bands at 1510—1550 cm.$^{-1}$ or 1000—1030cm.$^{-1}$ which could be attributed to $-NH_3$ frequencies.

Magnetic susceptibility (by W. E. GARDNER and J. PENFOLD). Gleu and Breuel [3] reported that ruthenium red is diamagnetic. The susceptibilities of our brown nitrate and red chloride were measured by the Faraday method with a Sucksmith ring balance and a tantalum standard at five different field strengths. Values of χ_g for the brown nitrate were $5{\cdot}60 \times 10^{-6}$ and $1{\cdot}44 \times 10^{-6}$ at 77° and 293° K respectively. On the assumptions that the factor θ in the Curie–Weiss law is zero and that the diamagnetic correction is negligible, $\mu_{eff.}$ is $2{\cdot}83 - \sqrt{77 \times 5{\cdot}60 \times 10^{-6} \times 1097/3} = 1{\cdot}13$ B.M. per ruthenium atom. For the red chloride, χ_g was $0{\cdot}75 \times 10^{-6}$ at 293° K and the corresponding value of $\mu_{eff.}$, on the same assumptions, is 0·77 B.M. per ruthenium atom. No significance in terms of unpaired electrons can be attributed to the absolute values of $\mu_{eff.}$; however, the difference $3(1{\cdot}13 - 0{\cdot}77) = 1{\cdot}1$ B.M., between $\mu_{eff.}$ for the three ruthenium atoms in the red and the brown complexes is consistent with a change in the sum of the oxidation states of the three ruthenium atoms from an even (+10) to an odd (+11) number.

Properties of Solutions.—Chlorine present as chloride ion. (*a*) Electromigration. Aqueous ruthenium red chloride (3×10^{-3}M-Ru) was placed in the centre compartment of an electromigration cell from which anode and cathode compartments were separated by sintered-glass discs. After 3 hr. at ~8 v/cm., 93% of the chlorine was in the anode compartment, all the red ion was in the cathode compartment, and the original liquid was colourless. (*b*) Solvent Extraction. An aqueous solution of ruthenium red chloride, after equilibration for 5 min. with an equal volume of 0·1M-di-(2-ethylhexyl) hydrogen phosphate in kerosene, lost its colour entirely (>99%) to the organic phase and retained all its chlorine (94%). The spectrum, $\lambda_{max.}$ 460 mμ ($\varepsilon_{Ru} \sim 12{,}000$), of the organic phase showed that there had been rapid atmospheric oxidation to the brown complex. These values were unaltered when the ruthenium was brought

back into an aqueous phase by equilibration with 0·1N-hydrochloric acid. They changed, however, to those for the red cation when the acid solution was brought to pH 9 with ammonia.

Charge on the red cation. This may be deduced from its extraction from aqueous solution by alkyl esters of phosphoric acid (the extraction of cations being related to a variable raised to the power of their charge); from its retention on cation-exchange resins; and from its dyeing natural fibres. A charge of about +6 (5·90 and 5·73) for the red cation of a specimen prepared in this work was found by Grinberg *et al.*[8] by ion-exchange. The equivalent conductivities of aqueous ruthenium red chloride at 21° c are 81, 105, 131, and 136 mhos at dilutions of one equivalent in 81, 401, 2017, and 4050 l.; Λ_∞ for the cation is therefore 136 − 70 (chloride contribution) = 66. Application of Ostwald's rule gives for $(\Lambda_{1024} - \Lambda_{32})/10{\cdot}8$ a value of $(124 - 61)/10{\cdot}8 = 5{\cdot}8$ for the charge on the red cation.

Stoicheiometry for Red Complex ⇌ *Brown Complex.*—The occurrence of three (or multiples of three) ruthenium atoms in the complex is established by the stoicheiometry of this equilibrium. To fresh solutions of ruthenium red chloride (5—10 mg.) in 1—2N-sulphuric acid (10—20 ml.) was added 0·005M-ceric sulphate. A sharp change from +0·35 to +0·8 v (Gleu and Hubold [9] found 0·55 v) between the platinum electrode and standard saturated calomel electrode occurred after 0·33, 0·33, and 0·32 equivalent of oxidant per ruthenium atom. Spectrophotometric measurements showed the red had been converted into the brown complex. Similar stoicheiometry (0·35 equiv.) was observed with ferric ion, although the potential change was less sharp. Oxidation by air was avoided by adding the solid to an excess of the ferric solution and back-titrating.

The brown products from some of these oxidations were back-titrated potentiometrically, in an atmosphere of nitrogen, to the red complex with 0·01N-titanous sulphate. After the addition of 0·30—0·35 equivalent of reductant per ruthenium atom the potential dropped to that for ruthenium red. Successive oxidations with Fe^{3+} and reductions with Ti^{3+} of the same solution were possible.

Average Oxidation Number of Ruthenium.—Most of the methods used to determine the oxidation number of ruthenium in its complexes are inapplicable to ruthenium red. In hydrochloric acid, it is not reduced by the stannous ion or zinc which convert Ru^{III} into Ru^{II} in some complexes. In hot sulphuric acid, ceric ions, although they oxidise all the ruthenium to the tetroxide, also oxidise some of the nitrogen-containing groups by reactions discussed below. In cold alkali, neither permanganate nor perruthenate oxidises all the ruthenium in the red complex to a definite state but gives mixtures of colourless Ru^{III} complexes, insoluble hydrated oxides, and Ru^{VI} complexes. With permanganate, 2·1 equivalents, and with perruthenate, 1·4 equivalents, were required to cause the disappearance of the 532 mμ peak in the spectrophotometric titrations.

When, however, ruthenium complexes are added to hot alkaline solutions of oxidising agents the ruthenium is oxidised specifically to Ru^{VI}, and Gall and Lehmann [10] applied this reaction at 100° to determine the oxidation number in ammine-free chloro-complexes with manganate ($MnO_4^{2-} \longrightarrow MnO_2 + 2e$). But with ruthenium red at 100° we found this procedure to fail through a catalytic decomposition of manganate by the colourless complexes formed, although this catalysis was insignificant by the ruthenate ion, RuO_4^{2-}, produced in the oxidation of $K_2[RuCl_5,H_2O]$. However, using a solution of $K_2[RuCl_6]$ added to manganate in the presence of ammonia, we have shown that catalysis is negligible at about 30°, and that the colourless ruthenium complexes so produced by oxidation (Found, 2·05 and 2·08 equiv. of manganate per Ru atom) are in the +6 state.

In the determination, to 15 ml. of 0·0028M-manganate in 2N-sodium hydroxide at 40°, 8 ml. of a solution ($3{\cdot}2 \times 10^{-3}$M-Ru) of the red chloride in 2N-ammonia were added. The mixture was centrifuged, then cooled to room temperature, and the optical density of the supernatant liquid determined from 385 to 650 mμ. The procedure was repeated with successive small additions of the ruthenium red solution:

Ruthenium red solution added (ml.)	8·0	9·0	9·5	9·8
Optical density at 605 mμ (for manganate)	0·67	0·27	0·12	0·04

The end-point (9·7 ml.) for the complete consumption of manganate was determined graphically.

[8] Grinberg, Trofimov, and Stepanova, *Radiokhimiya*, 1960, **2**, 78.
[9] Gleu and Hubold, *Z. anorg. Chem.*, 1935, **223**, 305.
[10] Gall and Lehmann, *Ber.*, 1927, **60**, 2491.

XUM

The precipitated manganese dioxide, which was not removed during the titration, held no ruthenium, nor was the element present in solution as RuO_4^{2-} or RuO_4^-, all of it having been converted into colourless Ru^{VI} complexes. The equivalents per ruthenium atom, 2·75 and 2·7 for the red chloride and 2·6 for the red nitrate, give 6—2·7 = 3·3 for the oxidation state of ruthenium. In a titration of the nitrate when an excess of ammonia was not present, 22% of the ruthenium appeared as RuO_4^{2-} and none as RuO_4^-.

The alkaline manganate was prepared by adding a slight excess of sodium formate to potassium permanganate in 2N-sodium hydroxide, stirring for 15 min., storage for 24 hr., and removal of the precipitated manganese dioxide by centrifugation. After acidification, the manganate solutions were standardised with ferrous sulphate.

Behaviour with Ceric Ion in Sulphuric Acid.—At room temperature ceric ion discharged the colour of ruthenium red when the average oxidation state reached +4·3 and some of the ruthenium was slowly deposited as oxide.

At 100°, instead of only the ruthenium being oxidised to tetroxide, as happens with other complexes,[11] much ceric ion was consumed in a side-reaction. Ruthenium red chloride was dissolved in 1—2M-sulphuric acid containing an excess of ceric sulphate and some silver sulphate to prevent interference from chloride ions. The mixture was boiled and the ruthenium tetroxide formed was carried by a stream of nitrogen into N-oxalic acid.[12] The amounts recovered were 70—95% of the total, as measured by the optical density at 375 mμ. The silver chloride was filtered off from the remaining liquid and the excess of oxidant titrated with ferrous sulphate. The ammonium ion was determined by boiling some of the solution with sodium hydroxide, and the nitrate by re-boiling the residual solution with Devarda's alloy. The equivalents of oxidant consumed per mole of cation varied (51, 63, 58, 36, 35, and 59) but always greatly exceeded the 14 required for oxidation from a +10/3 to a +8 state. Nitric acid was also present in the solution.

This behaviour is attributed to the formation of colourless amido-Ru^{VI} complexes, typified by $[RuO_2(OH)_2(NH_2)_2]^{2-}$ (III) in which all the nitrogen atoms are subsequently oxidised to nitric acid:

$$NH_2^- + 4O \longrightarrow NO_3^- + H_2O \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (I)$$

Ruthenium red has enough NH_2 groups for all the ruthenium to pass through the anion (III); this with Reaction 1 would require 62 equivalents and the fraction of nitrogen converted into nitric acid would be 6/14 = 0·43. One of the oxidations gave 63 equivalents, 0·5 of the nitrogen as nitric acid and 0·47 as ammonia, which is in quantitative agreement with the sequence. But the reaction is sensitive to variation in procedure, for in another the respective figures were 35, 0·18, and 0·83, indicating that ~40% of the ruthenium passed through the sequence and the balance was oxidised through RuO_4^{2-} to ruthenium tetroxide.

These colourless Ru^{VI} intermediates ($\varepsilon_{Ru} < 100$ at < 400 mμ) are those formed when ammonia is added to solutions of RuO_4^{2-}. Krauss [13] studied this reaction and obtained by evaporation an uncharacterised black product. We found that when the excess of ammonia was expelled at room temperature the atomic ratio N/Ru in the solution fell to *ca.* 2, and slowly to 1·9—1·6 when warmed. The ruthenium complexes in the solution are very stable. At 100° in 2·5N-sodium hydroxide, RuO_4^{2-} was not formed and very little hydrated ruthenium dioxide was precipitated after several hours; all the nitrogen was liberated only after prolonged boiling with Devarda's alloy. Solutions of the complexes in sulphuric acid were stable at 100° and consumed 10—12 equivalents of ceric ions per ruthenium atom with the formation of ruthenium tetroxide. This approximates to that expected by the stoicheiometry of Reaction 1 and the charge change $Ru^{VI} \longrightarrow Ru^{VIII}$.

Absorption Spectra and Deprotonation.—The Figure shows the spectrum, measured with a Unicam S.P. 500 spectrophotometer, at 20—22° of the red chloride in water and the brown nitrate in 0·01N-nitric acid. $\lambda_{max.}$ for the red cation increased by 3—5 mμ as the pH was raised from 7 to 10. As the wavelength of the point of intersection for mixtures of the red and brown cations also increased with pH, by *ca.* 10 mμ from pH 3 to 7, it is likely that $\lambda_{max.}$ for the brown cation is also a function of the acidity.

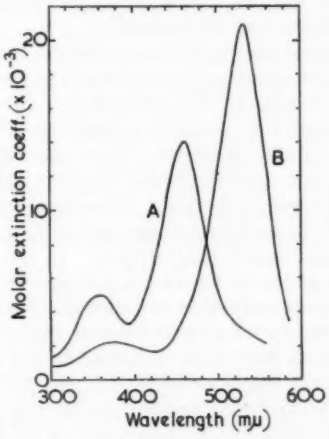
The brown nitrate is weakly acidic, and the pH, 4·6, of a solution of $11·4 \times 10^{-6}$ mole in

[11] Martin, *J.*, 1952, 2682.
[12] Mesaric and Branica, *Croat. Chem. Acta*, 1958, **30**, 81.
[13] Krauss, *Z. anorg. Chem.*, 1924, **132**, 301.

50 ml. of water implies that about 10% of the complex is ionised. Its spectrophotometric titration with sodium hydroxide ($13{\cdot}5 \times 10^{-6}$ mole for the complete conversion at pH 7·5 of the brown into the red complex), together with absence of change in the specific conductance ($\kappa = 195 \times 10^{-6}$ mho), is in accordance with the reaction:

$$[\text{Brown cation}]^{+7} + OH^- \longrightarrow [\text{Red cation}]^{+6} + OH \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

After addition of a further $11{\cdot}5 \times 10^{-6}$ mole of sodium hydroxide, the pH was 9·3 (cf. 10·4 calculated for no reaction) and κ had only increased to 197×10^{-6} mho. With another 25×10^{-6} mole of alkali, the pH was 10·3 and κ had increased to 262. This suggests that the red cation can also be deprotonated and that the small increases in $\lambda_{max.}$ with pH that occur for both cations are due to the formation in solution, by hydrogen bonding of water to ammine groups,[14] of cations of lower charge, *e.g.*, for the brown, $[Ru_3O_2(NH_3)_{14}]^{7+} \longrightarrow [Ru_3O_2NH_2(NH_3)_{13}]^{6+}$, and for the red, $[Ru_3O_2(NH_3)_{14}]^{6+} \longrightarrow [Ru_3O_2NH_2(NH_3)_{13}]^{5+}$.



Absorption spectra of:
A, *Brown complex in* 0·01N-*nitric acid.*
B, *Red complex in water.*

Oxidation by Air.—Spectrophotometry showed that acidic solutions of the red cation were oxidised to the brown cation not only by Ce^{4+}, Fe^{3+}, HNO_3, etc., but also by air (20% in 24 hr. in 0·1N-hydrochloric acid). Rapid oxidation has been observed [2] in 2N-hydrochloric acid. The rate of oxidation in air is favoured by conditions which tend to remove solvated water from the cation, such as heating of the solid or solvent extraction from aqueous solution.

Destruction of Structure.—Decolorisation of the red cation occurs both in acid and in alkaline solutions. At 80° in 2N-sodium hydroxide there was complete destruction of the cation in about 1 min., but even after long storage only 20—43% of the ruthenium was precipitated as hydrated dioxide, the remainder entering such complexes of Ru^{VI} as (III). Boiling for a few minutes with N-hydrochloric acid converted the red complex entirely into a pale yellow solution; the rapidity of the decomposition is attributed to the formation of strong chloro-complexes—the spectrum suggested those of Ru^{III}. In contrast, boiling with M-nitric acid produced the brown complex and little decomposition.

Discussion

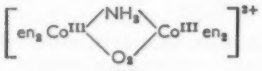
The evidence advanced in the last section has led to the formulation of ruthenium red as (I). Although there are no recorded complexes with structures analogous to this trinuclear oxo-bridged one, others show certain features in common with it. Thus the red complex [15] (IV) is diamagnetic and undergoes a reversible, one-electron oxidation, for which the potential varies considerably with pH, to a paramagnetic, green complex; the nitrate of the oxidised complex is also insoluble. The bluish-red complex (V) prepared by

[14] Adamson and Basolo, *Acta Chem. Scand.*, 1955, **9**, 1261.
[15] Thompson and Wilmarth, *J. Phys. Chem.*, 1952, **56**, 5.

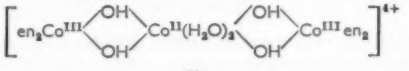
XUM

Werner [16] also shows resemblances: thus it appears as one of several products of a slow atmospheric oxidation of mononuclear complexes of the metal in a relatively low oxidation state and is decomposed by hydrochloric acid to mononuclear complexes.

A feature of ruthenium red is its lack of paramagnetism. Other complexes possessing



(IV)



(V)

this property are the binuclear $[Ru_2OCl_{10}]^{4-}$ which has the linear Ru–O–Ru, and the binuclear rhodo-chromium complex [17] $[Cr_2O(NH_3)_{10}]^{4+}$ which has the linear Cr–O–Cr. When the latter is modified by protonation of the oxygen atom, the erythro-complex formed is paramagnetic. Besides $[Ru_2OCl_{10}]^{4-}$, there are other complexes with ruthenium in oxidation states $> +3$ which are almost diamagnetic [6] and must be polynuclear complexes as yet uncharacterised.

Non-integral values for the oxidation state of ruthenium are not confined to the red and the brown complexes here described; they are found in a chloro-complex [18] (+3·5) and in aquo-complexes [19] (+4·2—4·6). The existence of several polynuclear complexes of ruthenium with low magnetic moments is therefore likely, and they will often be highly coloured as are the solutions of the aquochloro- and aquonitrato-complexes which gave rise to this work. For the former, Wehner and Hindman [4] proposed $[Ru^{IV}(OH)_2Cl_2(H_2O)_2]^0$: Joly [20] made from anhydrous ruthenium trichloride a solid likely to be the same violet complex; it formed ruthenium red with aqueous ammonia and was designated, first, $RuOH,Cl_2$ and later [1] $Ru_2(OH)_2Cl_2$. In our view it is more probably $[Ru_3O_2Cl_6(H_2O)_6]^0$ with the linear Ru–O–Ru–O–Ru grouping that occurs in ruthenium red.

We have not been able to determine fully the rôle of water in salts of the red and the brown complexes. Two molecules of water remain with each trinuclear unit up to about 85°; these may be loosely attached to the two bridging oxygen atoms, in the manner, shown by *X*-ray study, of water in $K_4[Ru_2OCl_{10}],H_2O$.

It is now clear that the ruthenium red chloride, and the various solids prepared by Morgan and Burstall [2] by treatment of its aqueous solution severally with HCl, HNO_3, HBr, HI, KBr, KI, $K_2RuNOCl_5$, and K_2PtCl_6, were contaminated with other ammines of ruthenium because alcohol was used for precipitation. Salts such as their chloro-iodide would be mixtures of the chloride and iodide of ruthenium red. In the light of our work, their other preparations * fall into two classes: (i) Purple salts, obtained from solutions of the red chloride by the addition of potassium salts, which are the iodide (VII), nitrosyl-ruthenium pentachloride (IX), and platinochloride of the ruthenium red cation in which another anion replaces chloride. (ii) Other salts, which are the chloride (II), bromide (V), and iodide (VIII) of the ruthenium brown cation mixed with salts of the other anions present in the solutions. For instance, the nitrate (III) contained chlorine and must have been a mixture of the brown nitrate and chloride.

The authors are grateful to Miss D. Rees for experimental assistance, to Dr. J. B. Sykes for translations of Russian and German papers, and to Professor P. L. Robinson for many helpful discussions.

Chemistry Division, Atomic Energy Research Establishment,
Harwell, near Didcot, Berks. [*Received, June 23rd,* 1960.]

* The Roman numerals are those given by Morgan and Burstall.[2]

[16] Werner, *Ber.*, 1907, **40**, 4426.
[17] Wilmarth, Graff, and Gustin, *J. Amer. Chem. Soc.*, 1956, **78**, 2683.
[18] Pshenitsyn and Ginzburg, *Zhur. neorg. Khim.*, 1957, **2**, 112.
[19] Cady, Ph.D. Thesis, University of California at Berkeley, U.S.A., 1957.
[20] Joly, *Compt. rend.*, 1892, **114**, 291.

383. *The Oxidation–Reduction Potentials of Some Copper Complexes.*

By B. R. James and R. J. P. Williams.

A method is described for determining the formal oxidation–reduction potentials of cuprous–cupric complexes. It is applied to a large number of copper complexes, mostly with 1,10-phenanthrolines, bipyridyls, and other nitrogenous bases. For a series of complexes with differently substituted phenanthrolines and bipyridyls the redox potentials are not simply related to the acid dissociation constants of the ligands. The effect of change of co-ordination number of the ions upon the redox potentials is described, and the causes of changes in co-ordination number are discussed.

This paper describes the determination of the oxidation–reduction potentials of a number of copper complexes. As in a previous paper on ferrous–ferric couples [1] the potentials measured are formal mid-point potentials, E'_f. They refer to reversible potentials in a solution of equal concentrations of the oxidised and the reduced form of the element, here cupric and cuprous ions respectively, at some fixed pH and ionic strength. No account has been taken of activity coefficients. (E'_f is the measured potential at an undefined degree of formation of the two complexes $Cu^{I}L_x$ and $Cu^{II}L_y$; E_f* refers to equal degrees of formation of the two complexes; E_f^0 is the standard potential, traditionally defined.) From the variations of potential with pH, the degree of complex formation is found so that the potentials, E_f*, for equal co-ordination of the two ions can be calculated.

Experimental

The procedure for determination of ferrous–ferric couples [1] was modified for cuprous–cupric couples. In the earlier work ferrous and ferric ions were introduced into an acid solution and in a chloride medium. Before the addition of the solid ligand to the solution (from a glass basket) all oxygen was removed from the cell dead-space. Cuprous ions disproportionate in aqueous solution and can only be stabilised by complex formation. In the present series of experiments therefore we made up cupric ion and ligand solutions separately and these were first put into the titration cell.[1] The final cupric-ion concentration was $1{\cdot}75 \times 10^{-4}$M; the ligand concentration depended on the system being investigated but was always at least 3·5 times the total copper concentration. The cuprous ion, as a weighed amount of cuprous chloride, was placed in a short-necked thin-glass bulb which floated on the surface of the cupric ion–ligand solution and was kept vertical by a glass rod which passed through an air-tight gland in the cell-cap. Pushing the rod enabled the bulb to be broken on the bottom of the titration cell. Before de-oxygenation of the cell and its contents the cupric–ligand solution was adjusted to a high pH, if necessary by the addition of sodium hydroxide. It was found advisable to bring the pH of the solution to about one unit above the acid dissociation constant, pK_a, of the ligand so that when the cuprous ion was added to the solution it was converted into its complex and did not disproportionate. The solution and dead-space of the cell were swept free from oxygen as described earlier.[1] This usually required 2—4 hr., after which time the bulb containing cuprous chloride was broken. The cuprous salt dissolved only slowly, especially in purely aqueous media, and the system was usually left overnight (about 12 hr.) before measurements were started. The pH and the E'_f of the solution were measured and subsequently a series of similar measurements were made over a wide range of pH.[1] The pH was adjusted by the addition of concentrated acid or alkali from a microsyringe. Generally the ionic strength of the solutions was held constant by making the aqueous solutions 0·1M in potassium sulphate and the water–dioxan solutions 0·3M in potassium nitrate. Sulphate or nitrate was chosen as a background salt as other anions were known either to form strong complexes with cuprous ions (*e.g.*, chloride), or to give insoluble precipitates with the metal complexes (*e.g.*, perchlorate forms an insoluble cuprous–phenanthroline complex). With both the amino-acid and

* Some of the results and part of the discussion in this paper were described at the Co-ordination Chemistry Conference in London, 1959. A summary appeared in the Abstracts of the Conference.

[1] Tomkinson and Williams, *J.*, 1958, 2010.

XUM

saturated amine systems (see below), ligand concentrations up to 1·25M were employed; the ionic strength is thus higher in these systems. Concentrations of ligands and ionic strengths are given in footnotes to the Tables.

Materials.—" AnalaR " dioxan was purified as described before.[1] Standard cupric solutions were made up by weighing " AnalaR " copper sulphate pentahydrate. Cuprous chloride was prepared by reduction of cupric chloride with aqueous sodium sulphite:[2] the white crystalline salt was stable indefinitely in a vacuum-desiccator.

Most of the phenanthrolines were obtained from the G. F. Smith Chemical Company, a few from British Drug Houses Ltd. They were recrystallised from hot water or benzene–light petroleum until the m. p.s agreed with those given by Smith *et al.*[3] 2-Methyl- and 2-chloro-1,10-phenanthroline had been prepared previously in this laboratory.[4] We prepared 5-amino-phenanthroline by reducing an alcoholic solution of the 5-nitro-compound with stannous chloride,[5] and the 4,7-dichloro-compound from the dihydroxy-compound by using phosphorus pentachloride.[6] In contrast to Synder and Freier's report [6] we isolated the dichloro-compound as a white solid which sublimed at about 240° (Found: Cl, 28·75. Calc. for $C_{12}H_6Cl_2N_2$: Cl, 28·4%). The 5-amino-compound was characterised by the spectrum of its 3 : 1 complex with ferrous ion, in agreement with Wilkins *et al.*[5] Wilkins *et al.*[5] also reported that the cuprous 2 : 1 complex with 5-aminophenanthroline is colourless. We found that the complex in 50% water–dioxan has an absorption maximum at 461 mμ (ε 6120). McCurdy *et al.*[7] stated that the intensely orange 2 : 1 complex of cuprous ion and 4,7-diphenyl-1,10-phenanthroline is converted into a colourless monocomplex at pH $< 7{\cdot}0$; we found that the 2 : 1 coloured complex existed even at pH 2·0. We cannot explain these discrepancies.

2,2′-Bipyridyl was obtained from British Drug Houses Ltd.; the dimethyl and diphenyl derivatives were obtained from the G. F. Smith Chemical Company.[8] The 4,4′-dicarboxy-derivative was prepared by oxidation of the dimethyl compound [9] and was characterised by the spectrum of the ferrous complex; [10] esterification gave the diethyl ester.[11] 2,2′-Bipyridyl-3,3′-dicarboxylic acid was prepared by oxidation of 1,10-phenanthroline by Bannick and Smith's method.[10] The properties of these compounds agreed with those in the literature. Other bipyridyls were prepared and characterised by Professor G. M. Badger.[12] 2,2′-Biquinolyl was a product from Hopkin and Williams Ltd. We are grateful to Dr. R. G. Wilkins (University of Sheffield) for a gift of 2,2′,2″-terpyridine. Morpholine (L. Light and Co.) was re-distilled before use; pyridine, quinoline, and aniline were redistilled commercial products. Other nitrogen-donor ligands and amino-acids were B.D.H. products, except diglycylglycine which was obtained from Roche Products Ltd.

" AnalaR " salts were used for buffers, and were dissolved in boiled-out water. The glass electrode was calibrated at pH 4·00 (25°) by 0·05M-potassium trihydrogen diphthalate, and at pH 9·185 (25°) by 0·05M-sodium borate.

Approximately 3N-sodium hydroxide (carbonate-free) was used as titrant in all the pH-titrations and in most of the redox experiments. " AnalaR " potassium trihydrogen diphthalate was the primary standard.

Results and Discussion

The theory of the method has been given earlier.[1] To illustrate its application we refer to Fig. 1, which consists of a series of plots of the measured potential E'_f against the pH meter reading, pB, for solutions of equal amounts of cuprous and cupric ion in the presence of excess of particular phenanthrolines. The curves consist of four parts. First, at W (highest pB), E_f is independent of pB. Here $\bar{n}_H$, the degree of formation of the

[1] *Inorg. Synth.*, 1946, **2**, 1.
[2] Smith and Banick, *Talanta*, 1959, **2**, 348.
[3] Irving and Mellor, *J.*, 1955, 3457.
[4] Wilkins, Schilt, and Smith, *Analyt. Chem.*, 1955, **27**, 1574.
[5] Snyder and Freier, *J. Amer. Chem. Soc.*, 1946, **68**, 1320.
[6] McCurdy and Smith, *Analyst*, 1952, **77**, 418, 846.
[7] Smith and Richter, " Phenanthroline Indicators," G. F. Smith Chem. Co., Columbus, Ohio, 1944, where a general discussion of many phenanthrolines and bipyridyls is given.
[8] Case, *J. Amer. Chem. Soc.*, 1946, **68**, 2574.
[9] Bannick and Smith, *Analyt. Chim. Acta*, 1958, **19**, 304.
[10] Case and Maerker, *J. Amer. Chem. Soc.*, 1958, **80**, 2745.
[11] Badger, *J.*, 1956, 616.

acid HL (where L is the phenanthroline), is zero. The pB is well above the pK_a of the ligand. The theoretical slope of the plot,

$$d(E'_f)/d(pB) = -\bar{n}_H\{\bar{n}_{II} - \bar{n}_I\}$$

is also zero. As pB is lowered the concentration of free ligand becomes dependent on hydrogen-ion concentration (*i.e.* on pB), the pK_a value is approached, and $\bar{n}_H$ becomes significantly greater than zero. $d(E'_f)/d(pB)$ takes on a real value, *i.e.*, greater than zero, approaching -1 as $\bar{n}_H$ reaches unity. Hence, over the second region, X, $(\bar{n}_{II} - \bar{n}_I) = 1{\cdot}0$; and as $\bar{n}_I = 2{\cdot}0$ (this is known independently), $\bar{n}_{II} = 3{\cdot}0$. At immediately lower pB values the slope $d(E'_f)/d(pB)$ approaches zero, $(\bar{n}_{II} - \bar{n}_I) = 0{\cdot}0$ (the third part of the plot, Y), and then becomes positive, reaching a value corresponding to $(\bar{n}_{II} - \bar{n}_I) = -1{\cdot}0$ (the fourth part of the plot, Z). For the cuprous–cupric systems we were unable to continue the titrations to still lower $\bar{n}$ values (degrees of complex formation), as the cuprous ion disproportionates. However, we have sufficient information to obtain both a large number of E_f^* values and, by using these and the slopes of the redox curves, the stability constants for cupric complexes. In all cases simple acid–base titrations were

FIG. 1.

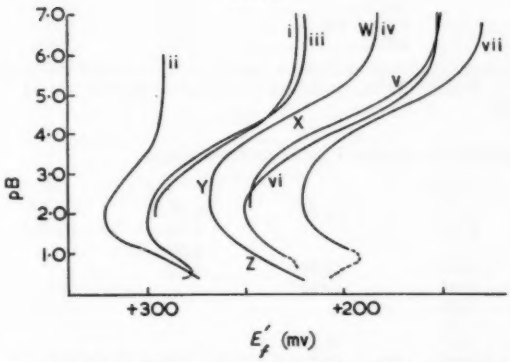


FIG. 2.

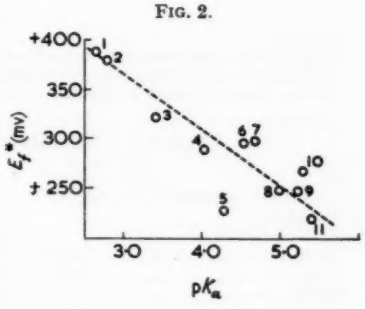


FIG. 1. *Redox potential–*pB *curves for a series of copper phenanthroline complexes in* 50% *dioxan–water solution. The phenanthrolines are*: i, *unsubstituted*; ii, 5-*chloro*; iii, 5-*methyl*; iv, 3,5,6,8-*tetramethyl*; v, 5,6-*dimethyl*; vi, 5-*amino*, vii, 4,7-*dimethyl*.

FIG. 2. *Dependence of the copper–phenanthroline couple potentials,* 2 : 1 *complexes, on the basicity of the ligands. The ligands are phenanthrolines,* viz.: (1) 4,7-*dichloro*; (2) 5-*nitro*; (3) 5-*chloro*; (4) 5-*phenyl*; (5) 4,7-*diphenyl*; (6) *unsubstituted*; (7) 5-*methyl*; (8) 5,6-*dimethyl*; (9) 5-*amino*; (10) 3,5,6,8-*tetramethyl*; (11) 4,7-*dimethyl*.

carried out on the ligand to determine pK_a values at the appropriate ionic strength, and in some cases the stability constants of cupric complexes were measured separately by standard methods in experiments separate from the redox titrations. The source of data in the Tables is noted.

The results will be given under the heading of the different ligands.

Water.—The standard reduction potential, E_f^0, of the Cu^{II}–Cu^{I} pair in water at an acid pH is given by Latimer [13] as 0·167 v. We have determined an experimental value of 0·148 v in 0·01N-sulphuric acid at 25° with 0·1M-potassium sulphate salt background: the potentials of a series of solutions, 10^{-2}M in Cu^{II} and of varying Cu^{I} concentration up to 10^{-4}M, were measured. In all cases the concentration of cuprous ion in solution was determined by using the 2,9-dimethylphenanthroline complex. No disproportionation occurred and the Nernst expression for potentials was obeyed. Extrapolation of the straight-line plot to equal concentrations of Cu^{II} and Cu^{I} gives the required E_f^0 potential.

[13] Latimer, "Oxidation Potentials," Prentice-Hall, New York, 1958, p. 175.

XUM

By a similar procedure the value of this potential in 50% dioxan–water is found to be 0.250 ± 0.01 v.

Phenanthrolines.—(a) *Substituents in 3,4,5-positions.* The most extensive series of measurements have been carried out on a group of substituted phenanthroline complexes. Most of these measurements were made in 50% dioxan–water. The potential–pH relations showed that in nearly all cases both cuprous and cupric ions formed complexes ML_2, but

TABLE 1. *Copper 1,10-phenanthroline couples.*

Potentials are expressed in millivolts and are the values determined at the degrees of formation indicated in parentheses, *i.e.*, E_f' ($\bar{n}_{II} : \bar{n}_I$).

Aqueous			50% *Dioxan–water*		
Subst. in ligand	pK_a	E_f^* (2 : 2)	Subst. in ligand	pK_a	E_f^* (2 : 2)
Unsubst.	4·97	+174	Unsubst.	4·53	+296
2-Cl	4·20	+400	4,7-Cl_2	~2·65	+387
2-Me	5·30	+337	5-NO_2	2·80	+379
2,9-Me_2	5·88	+594	5-Cl	3·43	+321
			5-Ph	4·03	+291
			4,7-Ph_2	4·30	+229
			5-Me	4·65	+299
			5,6-Me_2	5·00	+250
			5-NH_2	5·23	+248
			3,5,6,8-Me_4	5·30	+268
			4,7-Me_2	5·40	+220

In all the measurements with these ligands and those of Table 4 (see Tables 1—5), the following conditions were maintained: total ligand = 1.125×10^{-3}M; total cupric and total cuprous = 1.75×10^{-4}M. Ionic strength as stated in the text.

TABLE 2. *Stability constants for copper 1,10-phenanthrolines.*

Aqueous					
Subst. in ligand	log K_1^{II}	log K_2^{II}	log β_2^{II}	log K_3^{II}	log β_3^I
Unsubst.		6·64 [a]		4·94	15·82 [*]
				4·90 [a]	
"	8·82 [b]	6·57 [b]	15·39 [b]	5·02	
2-Cl	5·60	4·85	10·45		14·6
2-Me		6·20			16·95 [*]
		6·21 [a]			
"	7·4	6·4	13·8		
2,9-Me_2	~6·1	~5·6	11·7		19·1

50% *Dioxan–water*					
Subst. in ligand	log K_2^{II}	log β_2^{II}	log K_3^{II}	~log β_3^I/β_2^{II}	log β_2^I
Unsubst.			4·50	+0·77	
4,7-Cl_2		~10·2 [b]	3·25	+2·28	~12·5
5-NO_2			3·25	+2·15	
5-Cl		~11·0 [b]	3·72	+1·18	~12·2
5-Ph			4·05	+0·68	
4,7-Ph_2	~5·7		3·75	−0·35	
5-Me	~6·9		4·60	+0·81	
5,6-Me_2	7·15		4·93	0·0	
5-NH_2			5·02	−0·03	
3,5,6,8-Me_4	7·30		4·75	+0·30	
4,7-Me_2	~7·20		4·86	−0·50	

[*] Calculated from value for log β_2^{II} (Bjerrum, Schwarzenbach, and Sillén, "Stability Constants, Part I," *Chem. Soc. Spec. Publ. No.* 11, 1956). [a] Determined by spectrophotometric method.[4] [b] Determined by pH titration of cupric complex.

that at high free-ligand concentrations (high pB) the cupric ion gave a $Cu^{II}L_3$ complex (Fig. 1). The formal mid-point potentials, E_f^*, of the ML_2 couples are given in Table 1 and the stability constants of some of the complexes in Table 2. The pK_a values of the ligands are included in Table 3. In Fig. 2 the E_f^* (ML_2) values are plotted against pK_a. The lower valency state is stabilised relative to the higher at lower pK_a values, as found for the Fe^{II}–Fe^{III} pairs. The copper–phenanthroline potentials fall either above or below the value (0·25 v) for the hydrate pair in the mixed solvent. Taken together with

the effect of basicity of the ligand upon the potential, this result implies that the unsaturated nature of phenanthrolines stabilises cuprous with respect to cupric ion, but that the greater donor power of the phenanthroline-nitrogen atoms than of water stabilises cupric with respect to cuprous. A very similar situation was observed for iron complexes. It is not permissible, then, to say generally that phenanthrolines stabilise low-valency states though it does seem safe to conclude that increase in π-acceptor strength of phenanthrolines stabilises low-valent and increase in σ-donor strength of phenanthrolines stabilises high-valent complexes. On the other hand, a detailed inspection of Fig. 2 shows that even this generalisation is not applicable in a comparison between individual pairs of substituted phenanthrolines. Low potentials are observed for the systems with a 4- or 5-phenyl substituent. However, we believe that steric hindrance is present in these ligand molecules themselves.

TABLE 3. *Acid dissociation constants.*

(A) *Aqueous solution*

Ligand	pK_{NH^+}	pK_{CO_2H}	Lit.
(a) *Subst. in 1,10-phenanthrolines*			
Unsubst.	4·97 ± 0·02		4·96 (*a*)
5-NO_2	3·25 ± 0·10		(3·57) (*b*)
2-Cl	4·20 ± 0·02		
2-Me	5·30 ± 0·05		5·42 (*c*)
3,5,6,8-Me_4	5·80 ± 0·05		(5·54) (*d*)
2,9-Me_2	5·88 ± 0·02		(6·17) (*c*)
(b) *Subst. in 2,2′-bipyridyls*			
Unsubst.	4·50 ± 0·02		4·44 (*c*)
4,4′-Me_2	5·45 ± 0·02		
4,4′-$(CO_2H)_2$		pK_1K_2 ~ 7·6	
3,3′-$(CO_2H)_2$	≪3·0	3·0 4·63	
(c) *Other* N *bases*			
2,2′,2″-Terpyridine	3·99; 4·69		7·1; 7·1 (*e*)
Pyridine	5·52 ± 0·03		5·45 (*f*)
Quinoline	5·18 ± 0·05		
Aniline	4·80 ± 0·05		4·62 (*g*)
Ammonia			~9·0 (*h*)
Ethylenediamine	7·30 ± 0·05 9·83 ± 0·03		7·49 10·18 (*i*)
Morpholine	8·58 ± 0·03		8·70 (*f*)
Piperidine	11·25		11·28 (*f*)
Imidazole	7·01 ± 0·01		7·12 (*j*)

Ligand	pK_{NH^+}	pK_{CO_2H}	Lit.
(d) *Amino-acids*			
Glycine	9·53 ± 0·03	<3·0	9·62; 2·43 (*k*)
α-Alanine	9·62 ± 0·02	<3·0	(9·87; 2·34) (*l*)
Sarcosine	9·73 ± 0·03	<3·0	10·01; 2·24 (*k*)
Diglycylglycine	8·02 ± 0·02	3·30 ± 0·05	(8·09; 3·22) (*m*)
Polysarcosine	~8·7		
Histidine	6·16 9·05 ± 0·02	<3·0	6·05; 9·17 (*n*) (1·82) (*c*)

	pK_{NH^+}	pK_{SH}	pK_{CO_2H}	Lit.
(e) *Sulphur compounds*				
L-Cysteine	8·11	10·02	<3·0	8·48; 10·55 (*n*)
2-Mercaptoethylamine	8·30	10·95		8·35; 10·81 (*n*)
Thioglycollic acid		10·18 ±0·04	3·45 ±0·03	9·78; 3·58 (*n*)
Benzylidenebisthioglycollic acid			3·09 3·98	
Ethylenebisthioglycollic acid			3·19 3·81	

	pK values of the CO_2H groups	Lit.
(f) *Arsenic compound*		
Phenylarsinediacetic acid	3·61; 4·93	3·60; 5·03 at 20° (*p*)

TABLE 3. (*Continued.*)

(B) 50% v/v *Dioxan–water*

Ligand	pK_{NH^+}	Extrapolated val. for H_2O obtained by Smith (*d*)
(a) *Subst. in* 1,10-*phenanthrolines*		
Unsubst. ...	4·53 ± 0·03	(4·86)
4,7-Cl_2	2·65 ± 0·10	(3·03)
5-NO_2.....	2·80 ± 0·05	(3·57)
5-Cl	3·43 ± 0·03	
5-Ph	4·03 ± 0·03	(4·72)
4,7-Ph_2	4·30 ± 0·05	(4·84)
5-Me	4·65 ± 0·05	(5·23)
5,6-Me_2	5·00 ± 0·03	
5-NH_2	5·23 ± 0·03	
3,5,6,8-Me_4	5·30 ± 0·02	
4,7-Me_2	5·40 ± 0·02	pK_{OH}
4,7-$(OH)_2$ ...	11·5 ± 0·1	{ 7·28 ± 0·03 { 2·55 ± 0·05
(b) 2,2′-*Biquinolyl*	3·10 ± 0·10 3·64 (75% EtOH) (*q*)	

Ligand	pK_{NH^+}	
(c) *Subst. in* 2,2′-*bipyridyls*		
Unsubst.	3·62 ± 0·02	
5,5′-$(CO_2Et)_2$ ...	0·85 (spectra)	
5,5′-$(CO_2Me)_2$ ...	—	
4,4′-$(CO_2Et)_2$ ...	2·45 ± 0·10	
4,4′-Ph_2	3·25 ± 0·05	
5,5′-Me_2	3·97 ± 0·03	
4,4′-(phenethyl)$_2$	3·98 ± 0·05	
6,6′-Me_2.....	4·23 ± 0·02	
4,4′-Et_2.....	4·38 ± 0·02	
4,4′-Me_2.....	4·40 ± 0·03	
5,5′-Et_2-4,4′-Me_2	4·59 ± 0·03	
4,4′-$(CO_2H)_2$.....		pK_{CO_2H}
5,5′-$(CO_2H)_2$.....		4·25; 4·77 $pK_1 + pK_2 \sim 9·5$
(d) 8-Hydroxyquinoline (*r*)	4·13 ± 0·02	pK_{OH} 10·88 ± 0·03

References: (*a*) Pflaum and Brant, *J. Amer. Chem. Soc.*, 1954, **76**, 6215. (*b*) Brandt and Gullstrom, *ibid.*, 1952, **74**, 3532. (*c*) Ref. 4. (*d*) Schilt and Smith, *J. Phys. Chem.*, 1956, **60**, 1546. (*e*) Brandt and Wright, *J. Amer. Chem. Soc.*, 1954, **76**, 3082. (*f*) Bruehlman and Verhoek, *ibid.*, 1948, **70**, 1401. (*g*) Golumbic, *ibid.*, 1952, **74**, 5777. (*h*) Bjerrum, "Metal Ammine Formation in Aqueous Solution," P. Haase and Son, Copenhagen, 1947. (*i*) Bjerrum and Nielsen, *Acta Chem. Scand.*, 1948, **2**, 307. (*j*) Edsall, Felsenfield, Goodman, and Gurd, *J. Amer. Chem. Soc.*, 1954, **76**, 3054. (*k*) Basolo and Chen, *ibid.*, 1954, **76**, 953. (*l*) Monk, *Trans. Faraday Soc.*, 1951, **47**, 292. (*m*) Evans and Monk, *ibid.*, 1955, **51**, 1244. (*n*) Li and Manning, *J. Amer. Chem. Soc.*, 1955, **77**, 5225. (*o*) Albert, *Biochem. J.*, 1952, **50** 690. (*p*) Pettit, D.Phil. Thesis, Oxford, 1960. (*q*) Peard and Pflaum, *J. Amer. Chem. Soc.*, 1958, **80**, 1593. (*r*) Ref. 1 gives pK_{NH^+} 4·08, pK_{OH} 10·82.

Herbstein and Schmidt [14] have shown that all the individual rings in benzo[*c*]phenanthrene (I) are distorted out of the conventional stereochemical formulation to give relief from the "overcrowding" of hydrogen atoms at positions 1 and 2 (Fig. 3) (this was pointed out to us by Dr. J. Halpern). By analogy with this system, a 4(7)- or 5(6)-phenyl substituent in phenanthroline cannot undergo free rotation about a bond *xy* (cf. II), so that such a phenyl group is out of the plane of the phenanthroline molecule and its mesomeric effects will be modified. No steric hindrance can occur in 4,4′-diphenyl-2,2′-bipyridyl (III) and the potential of the copper couple is, as expected, higher than that for the parent 2,2′-bipyridyl system (see Table 4). A consideration of the ligand pK_a values and the corresponding copper potentials shows that the effect of an "out of plane" phenyl group is not simple.

The plot of pK_a against $\log K_3^{II}$ for the cupric complexes shows a general dependence on pK_a, the strongest bases forming the strongest complexes (Fig. 4). The few $\log K_2^{II}$ and $\log \beta_2^{II}$ values obtained suggest that similar considerations apply to these complexes (Table 2). The cupric–phenylphenanthroline complexes have exceptionally low stability. Presumably there is a rough linearity between $\log \beta_2^{II}$ and pK_a of the form

$$\log \beta_2^{II} \simeq a \,.\, pK_a + b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and similarly

$$\log \beta_2^{I} \simeq a' \,.\, pK_a + b' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

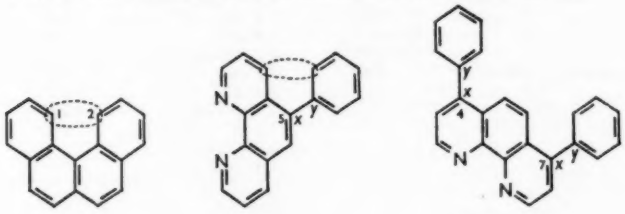
Such relations would account for the change in E_f^* with pK_a if $a > a'$ and $b' < b$. In an earlier paper [15] we have pointed out that, where approximately linear relations such

[14] Herbstein and Schmidt, *J.*, 1954, 3302.
[15] Jones, Poole, Tomkinson, and Williams, *J.*, 1958, 200.

as (1) and (2) are found, a is a useful measure of σ-acceptor strength and b a useful measure of π-donor strength of a cation.

(b) *Substituents in 2,9-positions.* 2,9-Substituents introduce considerable steric hindrance in the four-co-ordinate cupric complexes,[4,16] ML_2, which are usually planar. On the other hand, no steric hindrance is expected in the tetrahedral ML_2 cuprous complexes.[13] The potentials of the couples (Table 1) show how steric hindrance rather than basicity controls the relative stability of the two valency states. With these ligands no cupric

FIG. 3. *Steric hindrance in some aromatomic hydrocarbons, see text.*



(I) (II) (III)

FIG. 4. *The third step stability constant, K_3^{II}, of a series of cupric complexes compared with the basicity of the ligands. The ligands are listed as for Fig. 2.*

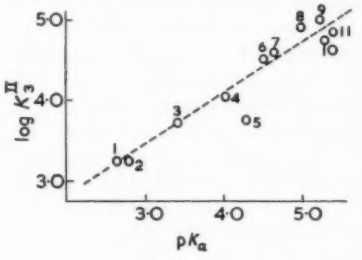
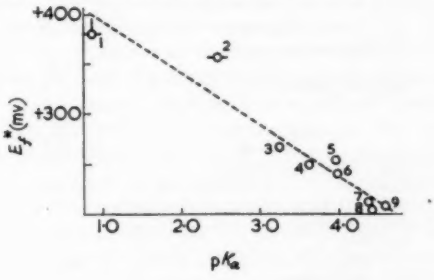


FIG. 5. *Dependence of the copper–bipyridyl couple potentials, 2 : 1 complexes, on the basicity of the ligands. The ligands are 2,2′-bipyridyls, viz.*: (1) *5,5′-diethoxycarbonyl*; (2) *4,4′-diethoxycarbonyl*; (3) *4,4′-diphenyl*; (4) *unsubstituted*; (5) *5,5′-dimethyl*; (6) *4,4′-diphenethyl*; (7) *4,4′-diethyl*; (8) *4,4′-dimethyl*; (9) *5,5′-diethyl-4,4′-dimethyl.*



complexes ML_3 were formed at the ligand concentrations used by us. The destabilisation of the Cu^{II} state is evident on examining the β_2^I/β_2^{II} ratios and the lower stability of these cupric–phenanthroline complexes than of the parent-base complexes (Table 2). These sterically hindered complexes will be more fully discussed in a later paper.

The cuprous complexes with 2(9)-substituted phenanthrolines show increasing stability with increasing basicity (Table 2).

Bipyridyl.—The change of E_f^* with ligand basicity in the bipyridyl series (ML_2 complexes; Table 4) is similar to that for phenanthrolines (see Fig. 5). For a given value of pK_a the bipyridyl couple has much the lower potential, indicating that bipyridyls stabilise the cupric relative to the cuprous ion more than does the corresponding phenanthroline. We attribute this difference to the weaker π-acceptor character of bipyridyl consequent on its lower conjugation. On the other hand, the 2,2′,2″-terpyridine, which is more highly conjugated, does not stabilise the cuprous ion as effectively as bipyridyl. The former

[16] Irving and Williams, *Analyst*, 1952, **77**, 813.

ligand, however, forms but a 1 : 1 complex with both the cuprous and the cupric ion: the Cu^{II} ion is co-ordinated to all three nitrogen atoms whereas this is unlikely for the Cu^{I} ion. This difference in co-ordination number would explain the strong stabilisation of the cupric state. 6,6′-Dimethyl-2,2′-bipyridyl and the similar ligand, 2,2′-biquinolyl,

TABLE 4. *Copper–bipyridyl couples.*

(A) *Aqueous*			(B) 50% *Dioxan–water*		
Subst. in 2,2-bipyridyl	pK_a	E_f* (2 : 2)	Subst. in 2,2′-bipyridyl	pK_a	E_f* (2 : 2)
Unsubst.	4·50	+120	Unsubst.	3·62	+251
4,4′-Me_2	5·45	+91	5,5′-Et_2-4,4′-Me_2	4·59	+210
4,4′-$(CO_2^-)_2$	—	+150	4,4′-Me_2	4·40	+204
		E_f* (1 : 1)	4,4′-Et_2	4·38	+215
3,3′-$(CO_2^-)_2$		+213	4,4-(Phenethyl)$_2$	3·98	+243
(2,2′,2″-Terpyridine)	4·69, 3·99	−80	5,5′-Me_2	3·97	+251
			4,4′-Ph_2	3·25	+269
			4,4′-$(CO_2Et)_2$	~2·45	+357
			5,5′-$(CO_2Et)_2$	0·85	~+380 ($\bar{n}_{II}$ ~2)
			4,4′-$(CO_2^-)_2$		+234
			4,4′-$(CO_2H)_2$		+300?
			5,5′-$(CO_2^-)_2$		+234
			6,6′-Me_2	4·23	>+750
			(2,2′-Biquinolyl)	~3·10	~+770

stabilise cuprous relative to cupric for much the same reason as that given for the relative stabilisation of cuprous by 2,9-substituted phenanthrolines. The rather limited number of stability constants determined for the copper bipyridyls indicates trends (Table 5) similar to those noted for the phenanthroline complexes.

TABLE 5. *Stability constants for copper bipyridyls.*

Aqueous

Ligand	log K_1^{II}	log K_2^{II}	log β_2^{II}	log K_3^{II}	log β_2^{I}
2,2′-Bipyridyl		~5·6		3·20	13·18 *
"	8·15[f]	5·50[f]	13·65[f]	3·30[f]	
4,4′-Me_2 deriv.				3·72	

50% *Dioxan–water*

Ligand	log K_2^{II}	log β_2^{II}	log K_3^{II}	log β_2^{I}/β_2^{II}	log β_2^{I}
Subst. in 2,2′-bipyridyl					
Unsubst.	~5·25			0·0	
5,5′-$(CO_2Et)_2$				+2·17	
4,4′-$(CO_2Et)_2$		~9·6		+1·80	~11·4
4,4′-Ph_2				+0·30	
5,5′-Me_2	5·48			+0·10	
4,4′-(Phenethyl)$_2$				−0·10	
4,4′-Et_2	~6·2		~2·9	−0·58	
4,4′-Me_2			3·25	−0·77	
5,5′-Et_2-4,4′-Me_2			~3·25	−0·67	
	log K_1^{II}	log K_2^{II}	log β_2^{II}	log K_1^{I}	log β_2^{I}
6,6′-Me_2	4·88[f]	~2·6	~7·48		~15·8
(2,2′-Biquinolyl) (aq.)	4·27	3·46	7·73		~16·5
2,2′,2″-Terpyridine (aq.)	~13·0[g]			~9·3	

[f, g] See Table 2.

Other Nitrogen-donor Ligands.—Ammonia forms a 4 : 1 cupric complex and a 2 : 1 cuprous complex.[17] The measured E_f value, at 25° in a 2M-ammonium nitrate background at a high pH, where both complexes are fully formed, was +1 mV, in excellent agreement with a value of 0·00 obtained by Bjerrum [17] at 18°. Our result and the cupric stability constants determined at 25° by Spike *et al.*[18] lead to a calculated potential E_f* for the two 2 : 1 complexes of +308 mV, cuprous ion binding the ligand the more strongly.

[17] Bjerrum and Nielsen, *Acta Chem. Scand.*, 1948, **2**, 307.
[18] Spike and Parry, *J. Amer. Chem. Soc.*, 1953, **75**, 3770.

XUM

With ethylenediamine both ions form a 2 : 1 complex, but the cupric ion is four-co-ordinated whereas the cuprous ion is but two-co-ordinated. This explains the very low potential (Table 6) of this couple, compared with those of the phenanthroline and bipyridyl couples.

TABLE 6. *Copper systems with other nitrogen donors. (Aqueous) E'_f ($\bar{n}_{II}$: $\bar{n}_I$) values.*

Ligand	pK_a	E'_f(1 : 2·5)	$E'_f(\bar{n}_I - \bar{n}_{II} = 2)$	E_f* (3 : 3)	E_f* (4 : 4)
Aniline	4·80	+240 (pL = 1·0)	+351 (pL = 1·45)	+304	~+300
Quinoline	5·18	—	—		
Pyridine	5·52	—	—		

Ligand	pK_a	E_f* (2 : 2)	E'_f (4 : 2)
Ammonia ...	9·0	+308	+1 (pL ~0·0)
Ethylene-diamine ...	7·30, 9·83	−360	
Morpholine ...	8·58	+250	
Piperidine ...	~11·25	(+145)?	

Ligand	pK_a	E_f* (2 : 2)
Glycine	9·53	−160
Alanine	9·62	−130
Sarcosine	9·73	~−130
8-Hydroxy-quinoline ...	4·13	~−375 *
Imidazole	7·01	+317
Histidine	9·05, 6·16	E'_f (2 : 1) = −170 †

* In 50% dioxan–water. † At pL ~2·5.

Measurements were made as follows: Total solution volume 80 ml. containing in each case total cupric = total cuprous = $1·4 \times 10^{-3}$ moles and total ligand (in moles) pyridine $3·0 \times 10^{-2}$, quinoline $1·72 \times 10^{-2}$, aniline $8·8 \times 10^{-3}$, morpholine $1·28 \times 10^{-2}$, piperidine $8·0 \times 10^{-2}$, ethylenediamine $8·0 \times 10^{-2}$, glycine $9·9 \times 10^{-2}$, alanine and sarcosine $9·9 \times 10^{-2}$ (in these cases the ionic strength was not controlled during the titrations, *i.e.*, there was no added salt); imidazole $8·0 \times 10^{-4}$, histidine $8·0 \times 10^{-4}$, ethylenebisdithioglycollic acid $1·0 \times 10^{-3}$, phenylarsinediacetic acid $1·0 \times 10^{-3}$ (in these cases the ionic strength was held constant by the salt background of 0·1M-potassium sulphate). Stability constants in Table 7 refer to the same conditions.

For a similar reason glycine, α-alanine, and sarcosine give very low potentials. The substituted amines, aniline and morpholine, like ammonia, bind cuprous more strongly than cupric ions at low $\bar{n}$ values. The cupric complexes are weak and in the morpholine system $\bar{n}_{II}$ only just reached 3 even with 1·0M-ligand; the potentials measured in this solution are positive relative to the hydrate couple whereas at this ligand concentration in the case of ammonia the potential is strongly negative with respect to the hydrate couple. Any explanation of these differences depends upon an understanding of the co-ordination of the two ions and it is not sufficient to state that a donor ligand such as a primary amine stabilises the high-valent state. In pyridine solutions the co-ordination of the two copper ions is not very different over a wide range of pH, and the 3 : 1 and probably the 4 : 1 complexes of both ions are formed. The cuprous ion is stabilised relative to cupric at all $\bar{n}$ values. For unsaturated ligands, then, the co-ordination number of the cuprous ion appears to be four rather than two. In quinoline solutions the co-ordination of the cupric ion is restricted to $\bar{n} \leqslant 2$ but that of the larger cuprous ion again approaches four. We presume that steric hindrance reduces the stability of the cupric complexes. With quinoline, as with sterically hindered phenanthrolines and bipyridyls, the copper couple potential is high.

With the imidazoles there is no evidence of a higher complex than 2 : 1 of cuprous ion, but cupric ion forms a 3 : 1 and a 4 : 1 complex. The E_f* (2 : 2) value shows that cuprous ion binds the ligand more strongly. Thus all the 2 : 1 copper complexes (with ammonia, pyridine, quinoline, aniline, morpholine, and imidazole) are more stable in the cuprous than the cupric form to about the same degree (~2 kcal./mole).

Histidine forms complexes with cupric and cuprous copper, but we and other workers [19] have found the systems somewhat complicated. Our work agrees with earlier findings [19] that at a high pH (pH ≈ 10 and pL ≈ 2·5) histidine forms a 2 : 1 chelate complex with cupric copper, presumably through the four nitrogen atoms. At the same pH the redox potential–pH curves (Fig. 6) indicate a 1 : 1 complex with the cuprous ion presumably co-ordinated through both the imino- and the amino-nitrogen atom. The potential of this system is very low (Table 6). At lower pH values (<7) it appears from the redox

[19] Leberman and Rabin, *Nature*, 1959, **185**, 747.

XUM

potential–pH curve (Fig. 6) that a 2 : 1 histidine–cuprous complex exists and the co-ordination of the cupric ion is still two. The Cu^{I} cation is presumably bound only through imino-nitrogen atoms. This is expected from a comparison with the cuprous–imidazole system. When the concentration of histidine is the same as that of the total copper, the

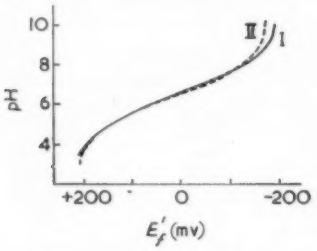


FIG. 6. *Redox potential–pH curves for copper–histidine complexes.* (I) *Total copper,* $3{\cdot}5 \times 10^{-4}$ *mole/l.; total ligand,* 10^{-2} *mole/l.* (II) *Total copper,* $3{\cdot}1 \times 10^{-3}$ *mole/l.; total ligand,* 10^{-2} *mole/l.*

cupric ion forms a 1 : 1 complex which hydrolyses at high pH.[19] Stability constants for the complexes are included in Table 7.

Sulphur and Arsenic Ligands.—We have found from a study of absorption spectra that the anionic species of ethylenebisthioglycollic acid forms a monomeric 1 : 1 cupric complex; the species is very probably as inset. The exact nature of the cuprous species is uncertain, but at low pH's when the ligand is fully protonated the cuprous ion is co-ordinated only to sulphur. Potentials measured at pH 1—5 are all + ~400 mv, indicating considerable stabilisation of the cuprous state. We attribute this in part to π-bond formation between the vacant outer *d*-orbitals of the sulphur atom and the fully filled 3*d*-orbitals of the cuprous ion, and in part to polarisation. The full interpretation of the redox curve involves the "early" dissociation of the carboxyl groups in the cuprous complex, *i.e.*, they are titrated at a lower pH than they are in the uncomplexed ligand (see Tables 3 and 7).

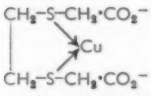


TABLE 7. *Stability constants of various copper complexes.*

Ligand	$\log_{10}$ (Stability constants)
	Aqueous
Pyridine	$\log K_1^{I} = 3{\cdot}90 \pm 0{\cdot}10$; $\log K_2^{I} = 2{\cdot}70 \pm 0{\cdot}10$
	$\log K_3^{I} = 1{\cdot}3 \pm 0{\cdot}2$; $\log K_4^{I} = 0{\cdot}8 \pm 0{\cdot}2$
	* $\log \beta_2^{I} = 8{\cdot}29$
,,	$\log K_1^{II} = 2{\cdot}52$, $\log K_2^{II} = 1{\cdot}86$, $\log K_3^{II} = 1{\cdot}31$, $\log K_4^{II} = 0{\cdot}85$
Glycine	$\log K_2^{II} = 0{\cdot}47$; * $\log \beta_2^{I} \sim 10{\cdot}0$
,,	$\log K_2^{II} \sim 1$; $\log \beta_2^{II} = 15{\cdot}2$
Alanine	$\log K_2^{II} \sim 0{\cdot}05$; * $\log \beta_2^{I} \sim 9{\cdot}6$
,,	$\log \beta_2^{II} = 15{\cdot}0$
Sarcosine	* $\log \beta_2^{I} \sim 9{\cdot}2$, using $\log \beta_2^{II} = 14{\cdot}6$
Imidazole	$\log K_1^{II} = 4{\cdot}33$, $\log K_2^{II} = 3{\cdot}28$, $\log K_3^{II} = 2{\cdot}7$, $\log K_4^{II} = 1{\cdot}9$
	$\log \beta_4^{II} = 12{\cdot}21$, $\log \beta_2^{I} = 10{\cdot}44$
,,	$\log K_1^{II} = 4{\cdot}20$, $\log K_2^{II} = 3{\cdot}47$, $\log K_3^{II} = 2{\cdot}84$, $\log K_4^{II} = 2{\cdot}0$
,,	$\log \beta_2^{I} = 10{\cdot}87$
Histidine	$\log \beta_2^{II}/\log K_1^{I} = 7{\cdot}62$, $\log K_1^{II} = 10{\cdot}3$ (pH titrn.)
,,	$\log K_1^{II} = 10{\cdot}5$
Ammonia	* $\log \beta_2^{I} = 10{\cdot}55$, using $\log \beta_4^{II} = 13{\cdot}05$ (Ref. 29)
Ethylenediamine	* $\log \beta_2^{I} = 11{\cdot}4$, using $\log \beta_2^{II} = 20{\cdot}0$ (Ref. 29)
Ethylenebisthioglycollic acid	$\log K_1^{II} \sim 4{\cdot}8$ (pH-titrn.); $\log \beta_n^{I} = 4{\cdot}37 + 2{\cdot}9n$ (pK_a values for the CO_2H groups in probable 1 : 1 Cu^{I} complex are 2·44, 2·71)
Phenylarsinediacetic acid	$\log K_1^{II} \sim 2{\cdot}5$ (ref. 24): $\log \beta_n^{II} = 3{\cdot}95 + 1{\cdot}7n$ (pK_a values for 1 : 1 Cu^{I} complex, are 2·70, 3·96)
	50% Dioxan–water
8-Hydroxyquinoline	* $\log \beta_2^{I} \sim 14{\cdot}7$, using $\log \beta_2^{II} = 25{\cdot}4$ and the unsteady E_f* value.

* $\log \beta^{I}$ values calc. from $\log \beta^{II}$ (Bjerrum, Schwarzenbach, and Sillén, "Stability Constants, Part I," *Chem. Soc. Spec. Publ. No.* 11, 1956); $\log \beta^{II}$ values calc. from those recorded for $\log \beta^{II}$. For ethylenediamine (Bjerrum, Schwarzenbach, and Sillén, "Stability Constants, Part I," *Chem. Soc. Spec. Publ. No.* 11, 1956) give $\log \beta_2^{I}$ 10·8.

XUM

Pettit [20] has shown that the cupric ion forms a 1 : 1 species with phenylarsinediacetic acid. Again we found that the cuprous ion is bound only through the arsenic atom at a low pH, and the redox curve is interpreted as for the previous sulphur system. The high potentials observed between +400 and +450 mv at pH 2·5—7·5 are similarly attributed to the described dative π-bonding and polarisation.

Several other ligands containing sulphur groups were examined, but they were oxidised by the cupric ion. The acid dissociation constants of the ligands are given in Table 3.

The Co-ordination Number of the Cuprous Ion.—The present work is in line with earlier suggestions that there is no simple co-ordination number for the cuprous ion. In combination with saturated ligands which are strong σ-donors and weak π-acceptors, *e.g.*, NH_3, it is 2-co-ordinate. With strong π-acceptors, *e.g.*, pyridine, phenanthroline, it is 4-co-ordinate. Four-co-ordination is also common in complexes with halides, $CuCl_4^{3-}$, and uncharged sulphur donors, $Cu^I[S{:}C(NH_2)_2]_4$. The chemistry of silver(I) complexes is similar: two-co-ordinated silver is particularly stable with ammines and four-co-ordinated in complexes with uncharged sulphur ligands.[21] The halide, thiocyanate, and cyanide complexes are somewhat intermediate in character: a high co-ordination number is found with π-acceptors. The two-co-ordination state of the cuprous ion with saturated ligands has long been attributed to *sp*-hybridisation, the energy gap between *s*- and *p*-states being so large in the Group IB elements as to prevent effective use of sp^3-hybridisation. An alternative explanation, the mixing of *s*- and *d*-states, can lead to the same result.[22] We favour the explanation given by Chatt [23] for the change to higher co-ordination number with the unsaturated ligands. The polarisation of ten 3*d*-electrons in a simple electrostatic field does not lead to crystal-field stabilisation. On molecular-orbital theory mixing of the *d*-states with ligand states will permit this polarisation provided the ligand is unsaturated; for, although there can be no energy gain from $d_\sigma\sigma_L$-mixing (L refers to a ligand orbital) where both d_σ and σ_L are full orbitals, there can be considerable gain from $d_\pi\pi_L$ mixing if π_L (the bonding or anti-bonding state of the ligand) are empty. Two linear bonds stabilise but one d_ϵ-orbital, whereas two such orbitals are stabilised in tetrahedral co-ordination.

The Co-ordination of the Cupric Ion.—The hydrated cupric ion is now considered to be 6-co-ordinate. In aqueous ammonia and ethylenediamine, only four of the water molecules of the hydrate are replaced readily, but it is known that a fifth and perhaps a sixth can be exchanged for ammine groups at very high ammine concentrations.[24] For non-aqueous solvents Graddon [25] has shown recently that five-co-ordination appears to be quite common [26] in cupric complexes but he found no evidence for six-co-ordination. In the present paper we have shown that in aqueous solutions of phenanthrolines and bipyridyls all six water molecules of the cupric complex ion are replaced relatively readily (Table 2). It is clear that the number of equivalent co-ordination positions about the cupric ion is not a simple number independent of the ligand.

We shall next consider those features of the ligand which we consider important in deciding the number of more or less equivalent ligand molecules taken up by the cupric ion. The size of the cupric ion is such that in the absence of polarisation it would be expected to be co-ordinated by six groups of the size of the oxygen or nitrogen atom. This can be deduced from Pauling's radius-ratio rules. Use of either an electrostatic or a molecular-orbital model for the polarisation of the ion, d^9 system, by the six ligands leads

[20] Petit, D.Phil. Thesis, Oxford, 1960.
[21] Ahrland, Chatt, Davies, and Williams, *J.*, 1958, 264, 276.
[22] Orgel, Tenth Solvay Conference, ed. Stoops, Brussels, 1956, p. 289.
[23] Chatt, "Chemistry of the Co-ordination Compounds," Pergamon Press, London, 1958, p. 515.
[24] Bjerrum, "Metal Ammine Formation in Aqueous Solution," P. Haase and Son, Copenhagen, 1941; ref. 17.
[25] Graddon, *Nature*, 1959, **183**, 1610.
[26] Llewellyn and Waters, *J.*, 1960, 2639; Cox and Corbridge, *J.*, 1956, 594.

XUM

to an energy separation of the $d_{x^2-y^2}$ and d_{z^2}-orbitals of the cupric ion (Jahn–Teller effect). Thus, either two or four of the six-co-ordination positions should be favoured starting from an octahedral field. Öpik and Price [27] considered that four positions were favoured rather than two, but Knox [28] pointed out that this is not necessarily so. In crystals, both distortions of the octahedron are known. However, none of these discussions make clear what is implied by the " field " of a ligand. On an electrostatic model the concept of the field of an uncharged ligand is the sum of the dipole and the induced dipole at the equilibrium distance of the ligand from the cation. The " field " on a molecular-orbital model is similar, being the sum of factors which are a property of the ligand alone and its polarisation due to the drift of electrons from the ligand orbitals into the empty cation orbitals (we consider π-bond formation later). Thus on either model the field contains a polarisation term which is very sensitive to interatomic distance. At short distances, therefore, a highly polarisable ligand, L_1, may form a more stable complex than a highly polar ligand, L_2, but at long distance the ligand L_2 would interact the more strongly. L_1 could be a nitrogen donor, *e.g.*, ammonia or phenanthroline, and L_2 an oxygen donor, *e.g.*, water. A large cation (*e.g.*, calcium) which is weakly polarising does not form co-ordination compounds with either ammonia or 1,10-phenanthroline in the presence of water. A small highly polarising symmetrical cation (*e.g.*, nickel), which undergoes equal polarisation in the six directions of an octahedron, forms six co-ordinate complexes, all six positions then interacting equivalently with the ligands. Now the fifth and the sixth position in the co-ordination sphere of the cupric ion behave as in the calcium ion, while the other four positions behave as in the nickel ion; that is to say, the order of preferred ligands at the fifth and the sixth position is $SO_4^{2-} > H_2O > NH_3$ as for calcium, whilst at the other four positions it is $NH_3 > H_2O > SO_4^{2-}$. From the interatomic distances in crystals we find that the cupric ion has a radius of approximately 1·0—1·1 Å perpendicular to the plane of the four most strongly held ligands (compare the radius of the calcium ion 0·97 Å), while in this plane the radius is but 0·70 Å. In the plane, polarisation of the ligand is of greater importance, while polarity is most important perpendicular to the plane. Primary amines, such as ammonia and ethylenediamine are more polarisable than water, and therefore the cupric ion takes up but four amine groups. The formation of complexes with unsaturated ligands requires the discussion of a further polarisation of the cupric ion. The six d_ϵ-electrons of the cupric ion are best stabilised by an octahedral field of six equal π-acceptor ligands. Unsaturated aromatic amines can fill this function. With such ligands the co-ordination number of the cupric ion will depend upon the relative importance of the two terms—the $d_\epsilon\pi_L$-bonding and the $d_\gamma\sigma_L$-bonding. In phenanthroline and bipyridyl complexes the latter is reduced in strength by the steric hindrance between two di-imine molecules held in the same plane. This can be seen from the values of log K_1 and log K_2 which are 8·8 and 6·5 for 1,10-phenanthroline and 8·1 and 5·5 for 2,2-bipyridyl, to be compared with 10·4 and 9·6 for ethylenediamine. Thus Jahn–Teller stabilisation must be lost in the 2 : 1 phenanthroline and bipyridyl complexes, and the cupric ion behaves more nearly as a spherically symmetrical ion, going on to add a third ligand. The lower stability of the cupric–phenanthroline and –bipyridyl complexes than the nickel complexes at the ML_2 and ML_3 stages, but not at the ML stage,[29] is due then to the matching of prefered directions of polarisation of the nickel cation with the ligand geometry and to the absence of such a match in the cupric complexes. As the Jahn–Teller stabilisation is present in the cupric hydrates, cupric complexes which cannot benefit from tetragonal distortion will always be unstable. The ligand-field stabilisation energy is sufficient to make the nickel complexes more stable than the cupric complexes only in the presence of such a steric selectivity. The more general case is that the greater

[27] Öpik and Price, *Proc. Roy. Soc.*, 1957, *A*, **238**, 425.
[28] Knox, *J. Chem. Phys.*, 1959, **30**, 991.
[29] Bjerrum, Schwarzenbach, and Sillén, " Stability Constants, Part I, Organic Ligands," *Chem. Soc. Spec. Publ. No.* 11, 1956.

polarising power of the cupric ion produces the stability order $Cu^{II} > Ni^{II}$, as is illustrated in the ML complexes of both phenanthroline and bipyridyl.

We are grateful to Professor G. M. Badger, Dr. H. Irving, and Dr. R. G. Wilkins for gifts of chemicals. The work was carried out while one of us (B. R. J.) held a D.S.I.R. research fellowship.

THE INORGANIC CHEMISTRY LABORATORY,
SOUTH PARKS ROAD, OXFORD.

[*Received, August 15th,* 1960.]

---

384. *Metal Complexes of Bis-[3-di(carboxymethyl)aminopropyl] Ether. The Computation of Stability Constants with the Aid of a High-speed Digital Computor.*

By H. IRVING and M. H. STACEY.

Values valid for 20° C and $\mu = 0{\cdot}1$M-KCl are reported for the stability constants of 1 : 1 metal complexes, ML, and protonated complexes, MHL, formed by bis-[3-di(carboxymethyl)aminopropyl] ether, H_4L, with a number of bivalent ions (Mg, Ca, Sr, Ba, Zn, Cd, and Hg).

Problems which arise in computing the "best" values for stability constants from titration data when mixtures of metal complexes, ML_j ($j = 1,2,\ldots N$), and a protonated complex, MHL, occur are discussed, and a programme for a high-speed digital computor to overcome the difficulties is described.

COMPLEXES of strontium with organic reagents are generally much weaker than those of calcium with the same ligand.[1] With ethylenediaminetetra-acetic acid (I; $n = 2$) (H_4Y) the stability constants are $K_{CaY} = 10^{10{\cdot}7}$ and $K_{SrY} = 10^{8{\cdot}63}$, respectively, so that the calcium complex is the more stable by about one hundred times. The removal of ingested strontium-90 would be simplified if a reagent, H_nZ, could be synthesised for which the ratio K_{CaZ}/K_{SrZ} was small (and ideally less than unity) while the complex-forming power for strontium remained high.

(I) $A_2N{\cdot}[CH_2]_n{\cdot}NA_2$ $A_2N{\cdot}[CH_2]_n{\cdot}X{\cdot}[CH_2]_n{\cdot}NA_2$ (II) $A = CH_2{\cdot}CO_2H$

Schwarzenbach has published data for a number of analogues of EDTA (I; n = 2) in which the chain separating the two chelating groups, NA_2, is extended either (*a*) by additional methylene groups (I; $n = 3$—8), or (*b*) by additional methylene groups joined through a symmetrically placed donor atom (II; X = O, $n = 2$, 3, or 4; or X = S, S–S, or NMe, $n = 2$).[2] In the first group, the increase in the size of the chelate ring produces the expected decrease in stability of both the calcium and the strontium complex,[3] but the relative stability for complexes of, *e.g.*, trimethylenediaminetetra-acetic acid (I; $n = 3$), *viz.*, $K_{CaY}/K_{SrY} = 10^{7{\cdot}12}/10^{5{\cdot}18}$ is still about 100 : 1. On the other hand, with the triamine (II; X = NMe, $n = 2$) the stability of the strontium complex had increased relative to that of the calcium complex for now $K_{CaY}/K_{SrY} = 10^{9{\cdot}55}/10^{8{\cdot}35} = 16$. The effect was even more striking with the hexadentate ligand (II; X = O, $n = 2$) for which $K_{CaY}/K_{SrY} = 10^{10{\cdot}0}/10^{9{\cdot}34} = 4{\cdot}6$. Unfortunately, studies with analogues of (II) were limited to measurements of the stabilities of the calcium (and sometimes the cadmium and mercury) complexes. In the present paper we extend the range of data for the complexone (II; X = O, $n = 3$) by reporting values for the stabilities of its complexes with magnesium, calcium, strontium, barium, zinc, cadmium, and mercury.

[1] Irving, *Chem. Soc. Spec. Publ.*, No. 13, 1959, p. 13.
[2] Schwarzenbach, Senn, and Anderegg, *Helv. Chim. Acta*, 1957, **40**, 1886.
[3] Irving, Williams, Ferrett, and Williams, *J.*, 1954, 3494.

XUM

Experimental

Bis-[3-di(carboxymethyl)aminopropyl] Ether (II; X = O; $n = 3$).—The sample used in earlier measurements [2] was made available to us by Professor Schwarzenbach. It had remained reasonably pure (M, by titration, 411. Calc. for $C_{14}H_{24}O_9N_2,2H_2O$: M, 400·4) and after being recrystallised from water a redetermination of its acid dissociation constants gave values ($pK_1 = 2·0$, $pK_2 = 2·74$, $pK_3 = 9·64$, $pK_4 = 10·14$) in good agreement with those reported by Schwarzenbach, Senn, and Anderegg,[2] *viz.*, 2·1, 2·7, 9·67, and 10·17, respectively. The values found for the stability constants of its calcium complexes CaY and CaHY (Table) (concentration constants valid for 20° and a constant ionic strength of 0·1M-potassium chloride) were identical with those previously reported [2] under the same conditions.

Potentiometric titrations were carried out with a glass electrode (Beckman Type H) in a double-walled vessel maintained at 20·0° with water pumped from a thermostat bath. Magnetic stirring was used. The saturated calomel reference electrode (also at 20°) was connected through a bridge of 0·1M-potassium chloride. The pH-meter (Radiometer PHM4) was calibrated with 0·05M-potassium hydrogen phthalate, and the slope for the glass electrode was checked at intervals by comparison with a hydrogen electrode. Carbonate-free potassium hydroxide [4] and all metal solutions were made up to an ionic strength of 0·1M with potassium chloride. The concentration, C_M, of stock solutions of metal salts ("AnalaR") was determined by titration against standard EDTA. The initial total volume was always 100 ml. and the concentration of ligand acid, C_A, was $1·07 \times 10^{-3}$M. The results of typical titrations are tabulated.

(a) *Reagent alone.* $C_A = 0·001070$M.

a	0·000	0·194	0·388	0·582	0·776	0·970	1·164	1·357	1·560	1·746	2·150	2·520
pH ...	2·794	2·814	2·895	2·955	3·026	3·108	3·207	3·333	3·503	3·780	8·733	9·443
a	2·325	2·720	2·910	3·105	3·300	3·495	3·690	3·880	3·980	4·160	4·355	4·580
pH ...	9·183	9·626	9·778	9·914	10·040	10·158	10·280	10·401	10·456	10·573	10·684	10·781

(b) *Reagent,* $C_A = 0·001070$, *and various metals.*

C_M/C_A	Mg = 2	Ca = 1·7	Sr = 2	Ba = 2	Zn = 1	Cd = 1
a	pH	pH	pH	pH	pH	pH
0·970	3·110	3·103	3·102	3·094	3·044	3·108
1·164	3·213	3·203	—	—	3·118	3·205
1·357	—	—	3·323	3·317	3·204	3·327
1·560	3·504	3·502	3·496	3·487	3·300	3·492
1·746	3·777	3·784	3·766	3·760	3·415	3·726
2·150	7·605	7·316	8·171	8·348	3·737	4·417
2·325	8·110	7·755	8·590	8·769	3·968	4·638
2·520	8·460	8·044	8·841	9·013	4·298	4·798
2·720	8·714	8·260	9·021	9·187	4·820	4·944
2·910	8·930	8·446	9·172	9·342	5·636	5·084
3·105	9·130	8·621	9·309	9·466	6·282	5·231
3·300	9·315	8·794	9·450	9·596	6·692	5·394
3·495	9·502	8·977	9·592	9·735	7·056	5·602
3·690	9·695	9·188	9·753	9·880	7·567	5·916
3·880	9·905	9·453	9·933	10·052	8·890	7·912
3·980	10·013	9·621	10·042	10·148	9·607	9·450
4·160	10·200	10·015	10·272	10·343	10·110	10·028
4·270	10·350	10·192	—	10·435	—	—
4·355	10·448	—	10·484	—	10·456	10·397
4·550	10·613	—	10·648	—	—	—
4·460	—	10·486	—	10·610	10·567	10·515

Values of pH for $a < 0·97$, not used in the calculations, have been omitted.

The Stability of the Mercuric Complex.—Solutions of mercuric nitrate and ligand acid contained in stoppered Pyrex test-tubes (50 ml.) were made up to a total ionic strength of 0·1M with sodium nitrate, and the pH was adjusted to different values between 3 and 6 by the addition of drops of 0·1M-potassium hydroxide or -nitric acid. A drop of mercury was added to each tube, the stoppers were inserted, and after being thoroughly shaken the tubes were transferred to a thermostat. Each tube had a stout platinum wire sealed through the bottom, and the progress of equilibration was followed at intervals by measuring $pHg = -\log_{10}[Hg^{2+}]$. The test-tube was removed from the thermostat bath, contact was made through a pool of

[4] Schwarzenbach and Biedermann, *Helv. Chim. Acta*, 1948, **30**, 331.

mercury to the internal mercury electrode, and the circuit completed through a bridge of 0·1M-sodium nitrate and a saturated calomel electrode. A precision potentiometer (Messrs. Cambridge Instrument Co.) was used and the pH of the solution was measured simultaneously with a glass electrode. The details of procedure have been fully described by Schwarzenbach and Anderegg.[5] Typical results are tabulated. The average value of log K(I) (=log K_{HgY} − pK_3 − pK_4) is 1·89 ± 0·05, whence log K_{HgY} = 21·67 ± 0·05.

10^4C_A	8·73	8·73	11·23	11·23	15·68	15·68	15·68	15·68
10^4C_M	3·07	3·07	6·14	6·14	5·86	5·86	5·86	5·86
pH	4·93	4·02	3·92	3·70	4·81	4·03	4·60	3·82
log K(I)	1·86	1·96	(2·01)	1·86	1·96	1·86	1·90	1·86

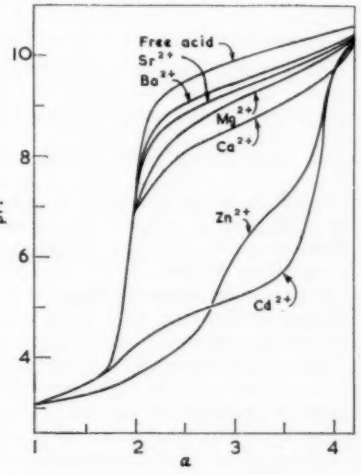
The acidity constant of the protonated complex HgHY was determined by titrating a solution of the mercury complex of the ether-acid (II; X = O; n = 3) with 0·1M-potassium hydroxide at 20° and μ = 0·1M-sodium nitrate. The curve near the end-point did not conform exactly to the theoretical shape and only the approximate value K^{H}_{HgHY} = 3·5 ± 0·2 was obtained, whence log K^{Hg}_{HgHY} = log K^{H}_{HgHy} + log K_{HgY} − pK_4 = 15·0 ± 0·2.

The Cadmium Complex.—In addition to the determination of the stability constant of the cadmium complex, K_{CdY}, by potentiometric determination, its value was also determined with the mercury electrode,[5] with the following results:

10^4C_{Cd}	10^4C_{Hg}	10^4C_L	pH	pHg	log K(II)
10·40	6·25	13·71	4·21	10·186	(−6·50)
10·40	6·25	13·71	4·56	10·722	−7·07
10·40	6·25	13·71	4·75	10·949	−7·32
12·25	6·13	13·45	4·72	10·864	−7·45
12·25	6·13	13·45	4·76	10·911	−7·50
14·00	6·00	13·20	4·76	10·836	−7·56

From the average value we have log K(II) = log K_{HgY} − log K_{CdY} = 7·38 ± 0·19, whence log K_{CdY} = 14·29 ± 0·20.

Titration curves for acid (II; X = O, n = 3).



Computation of Results

The titration curves (see Figure) show that complex formation with the alkaline-earth metals begins when the third buffer region is reached, where the ligand is present mainly as HY^{3-}. It thus becomes necessary to consider the occurrence of both the normal 1 : 1 complex MY^{2-} (where M is a bivalent cation) and the protonated complex MHY^{-}. Higher complexes (*e.g.*, MY_2^{6-}) and polynuclear complexes (*e.g.*, M_2Y, M_2HY^{+}) should not occur under the experimental conditions used. This assumption is supported by the results of Schwarzenbach

[5] Schwarzenbach and Anderegg, *Helv. Chim. Acta*, 1957, **40**, 1773.

et al.[3] for analogous complexones (obtained by using a metal : ligand ratio of 1 : 10) for which values of log $K^{M}_{M_nY}$ only reach 2—3 units when a chelate ring greater than seven-membered would otherwise be formed: in other cases it was too small to be measureable.

From the equations for mass-balance and electroneutrality, *viz.*,

$$C_A = [H_4Y] + [H_3Y^-] + [H_2Y^{2-}] + [Y^{4-}] + [MY^{2-}] + [MHY^-] \quad . \quad . \quad (1)$$

$$C_M = [M^{2+}] + [MY^{2-}] + [MHY^-] \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$[K^+] + [H^+] + 2[M^{2+}] = [H_3Y^-] + 2[H_2Y^{2-}] + 3[HY^{3-}] + 4[Y^{4-}] + 2[MY^{2-}] + [MHY^-] + [X^-] + [OH^-] \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $[K^+] = aC_A$ is the concentration of potassium ions introduced during the titration and $[X^-] = 2C_M$ is the concentration of univalent anion arising from the salt of the bivalent metal M, we obtain:

$$(4 - a)C_A - [H^+] + [OH^-] = 4[H_4Y] + 3[H_3Y^-] + 2[H_2Y^{2-}] + [HY^{3-}] + [MHY^{2-}] \quad (4)$$

$$[M^{2+}] = C_M - C_A + \alpha_H[Y^{4-}] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$[Y^{4-}] = \frac{(4 - a)C_A + [H^+] - [OH^-]}{\beta_H + ([M^{2+}][H^+]K_{MHY}/K_4)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where

$$\alpha_H = \frac{[H^+]^4}{K_1K_2K_3K_4} + \frac{[H^+]^3}{K_2K_3K_4} + \frac{[H^+]^2}{K_3K_4} + \frac{[H^+]}{K_4} + 1$$

$$\beta_H = \frac{4[H^+]^4}{K_1K_2K_3K_4} + \frac{3[H^+]^3}{K_2K_3K_4} + \frac{2[H^+]^2}{K_3K_4} + \frac{[H^+]}{K_4}$$

$$K_{MY} = [MY^{2-}]/[M^{2+}][Y^{4-}]; \quad K_{MHY} = [MHY^-]/[M^{2+}][HY^{3-}];$$

and

$$K_n = [H^+][H_{4-n}Y^{n-}]/[H_{5-n}Y^{1-n}]$$

The degree of formation of the metal complexes is defined by

$$\bar{n} = ([MY^{2-}] + [MHY^-])/([M^{2+}] + [MY^{2-}] + [MHY^-])$$

$$= (C_A - \alpha_H[Y^{4-}])/C_M \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

whence

$$\bar{n} + (\bar{n} - 1)[H^+][Y^{4-}]K_{MHY}/K_4 + (n - 1)[Y^{4-}]K_{MY} = 0 \quad . \quad . \quad . \quad . \quad (8)$$

The evaluation of the constants K_{MY} and K_{MHY} proceeds from the solution of a series of equations of the form (8) which relate values of $\bar{n}$, $[Y^{4-}]$, and $[H^+]$ for each point on the experimental titration curve. It will be appreciated that the computation of $[Y^{4-}]$ (and thence that of $\bar{n}$) by equations (6) and (7) involves a foreknowledge of the value of K_{MHY}. The computation is started by assuming $K_{MHY} = 0$ as a first approximation. Values of $[Y^{4-}]$ and $\bar{n}$ for each experimental value of $[H^+]$ and the corresponding degree of neutralisation, a, are then computed from equations (6) and (7) and substituted into equation (8). The sets of simultaneous equations are then solved to give approximate values for the constants K_{MY} and K_{MHY}. By using an average value of K_{MHY} obtained in this way better values of $[Y^{4-}]$ and $\bar{n}$ can now be calculated from equations (6) and (7) and substituted into equation (8). The new sets of simultaneous equations are then solved to give improved values for the two stability constants, and the process of successive approximation continued until no further improvement occurs. When an electrical desk calculating machine is used, the time occupied by the calculations for a single metal–ligand system may be as long as 80 hr.

Use of a High-speed Digital Computor

We have therefore developed for use with this University's high-speed digital computor "Mercury" a programme which can deal with these calculations or indeed with the complex problem of a metal ion in equilibrium with a 1 : 1 complex ML, its protonated complex, MHL, and a series of higher complexes ML_2, ML_3, $\cdots$ ML_N. (For simplicity we shall now omit

charges on the various species.) For a polybasic ligand acid, H_BL, the fundamental equations become:

$$[M] = (C_M - C_A + \alpha_H[L])/\{1 - (\beta_2[L]^2 + 2\beta_3[L]^3 + \cdots + (n-1)\beta_n[L]^n)\} \quad (9)$$

$$[L] = \{(B - a)C_A - [H] + [OH]\}/\{\beta_H + ([M][H]K_{MHL}/K_B)\} \quad . \quad . \quad . \quad . \quad (10)$$

$$\bar{n} = \frac{([H][L]K_{MHL}/K_B) + \beta_1[L] + 2\beta_2[L]^2 + \cdots + n\beta_n[L]^n}{1 + ([H][L]H_{MHL}/K_B) + \beta_1[L] + \beta_2[L]^2 + \cdots + \beta_n[L]^n} \quad . \quad . \quad . \quad (11)$$

$$= (C_A - \alpha_H[L])/C_M \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$\bar{n} + \{(\bar{n} - 1)[H][L]K_{MHL}/K_B\} + (\bar{n} - 1)\beta_1[L] + (\bar{n} - 2)\beta_2[L]^2 + (\bar{n} - n)\beta_n[L]^n = 0 \quad (13)$$

where $\alpha_H = 1 + ([H]/K_B) + ([H]^2/K_{B-1}K_B) + \cdots + ([H]^B/K_1K_2 \cdots K_B)$;

$\beta_H = ([H]/K_B) + 2([H]^2/K_{B-1}K_B) + \cdots + B([H]^B/K_1K_2 \cdots K_B)$;

$K_{MHL} = [MHL]/[M][HL]$; $\beta_n = [ML_n]/[M][L]^n$; and

$K_n = [H][H_{B-n}Y]/[H_{B+1-n}Y]$.

As already stated, the calculation of [L] requires a foreknowledge of K_{MHL} and as a first approximation this is set equal to zero. Values of [L] are then calculated from equation (10), and values of $\bar{n}$ from equation (11). Equations of the form (13) are now set up, using the experimental values of [H] and these approximate values of [L] and $\bar{n}$. The complete set of simultaneous equations is then solved by the method of least squares (for which a standard sub-routine is available in the computor programme) to give the best values for K_{MHL} and for each of the overall constants β_1 ($= K_{ML}$), β_2 ($= K_{ML}K_{ML_2}$), $\cdots$ and β_n ($= K_{ML}K_{ML_2} \cdots K_{ML_n}$). Being given a first approximation to the value of K_{MHL}, calculated values of [L] could then be improved in the following way. The value of [L] obtained from equation (10) depends on that of [M]; but this itself is a function of [L] [cf. equation (9)]. If the term [M] were to be eliminated from equations (9) and (10) there would result a polynomial in [L] of the second or higher degree for which no simple formula is available for evaluation of its real root. Advantage could be taken here of the speed of the electronic computor to find a value for [L] to satisfy both equations (9) and (10) by an iterative method.

A value of [M] computed from equation (9) (by using values of $\beta_2, \cdots \beta_n$ previously computed together with the value of [L] calculated for the approximation $K_{MHL} = 0$) is inserted into equation (10), and the value of [L] is computed by using the approximate value of K_{MHL} found as described above. This new value of [L] is used to calculate [M] from equation (9), and the iterative process is continued until successive values of [L] differs by less than 0·5%. This precision could not always be attained for certain values of pH, especially if the term $[M][H]K_{MHL}/K_B \geqslant \beta_H$, and at a later stage in the development of the programme a machine instruction was included to prevent more than 100 iterations being performed for any point on the titration curve. If this provision was not included the computor might " stick " at this stage in the calculations.

When consistent values of [L] and $\bar{n}$ have been obtained for each value of a and [H], the sets of simultaneous equations of the form (13) are set up and solved as before by a least-squares method, to give improved values of K_{MHL} and for $\beta_1, \beta_2, \cdots \beta_n$. With this second approximation to the value of K_{MHL} and the other stability constants the whole cycle of calculations is repeated automatically.

A difficult point of procedure was the inclusion of a satisfactory criterion for terminating the operations of the computor. Although we do not now believe it to be the best solution, the following procedure formed a chapter in the programme we used. Values of $\bar{n}$ were first computed from equation (11) by using experimental values of [H], the sets of constants K_{MHL}, β_1, β_n to be tested, and the corresponding corrected values of [L]. Thence theoretical values of $[L]_{calc.}$ were computed from equation (12) and substituted into equation (10) after this had been rearranged in the form

$$a_{calc.} = [B]C_A - [H] + [OH] - [L]_{calc.}\{\beta_H + ([M][H]K_{MHL}/K_B)\}]/C_A \quad . \quad (10a)$$

The values of the differences between calculated and observed degrees of neutralisation are then found and the machine was instructed to print out the root-mean-square deviation

$$d = \sqrt{(a_{calc.} - a_{obs.})^2/(\text{no. of observations} - 1)}$$

after each successive set of constants, K_{MHL}, $\beta_1, \cdots \beta_n$, had been computed. As the fit of the calculated curve to that of the experimental curve improved, the value of d decreased to a constant value which generally lay between 0·05 and 0·01. The number of iterations needed to compute the values finally adopted varied from three (when $K_{ML} \gg K_{MHL}$) to twelve (when $K_{MHL} \approx K_{ML}$). The accuracy of the final constants will depend on the relative magnitudes of the terms in equation (13). Thus the relative accuracy of determination of K_{MHL} and K_{ML} depends on the ratio $([H]K_{MHL}/K_B) : K_{ML} = [H]K^H_{MHL}$, where K^H_{MHL} is the equilibrium constant for the process $ML + H \rightleftharpoons MHL$ and is a measure of the tendency of the 1 : 1 complex to take up a proton. If the ratio $[MHL]/[ML] = [H]K^H_{MHL}$ is less than unity, the value of K_{ML} can be determined with high accuracy and that of K_{MHL} to lower accuracy. This is the case with the complexes of our ether-acid (II; X = O, n = 3) with cadmium, but not with the alkaline-earth metals for which $[H]K^H_{MHL} > 1$ until pH > 9, *i.e.*, until the degree of neutralisation is over 2·7 (with Ba^{2+}) or 3·3 (with Ca^{2+}). In some cases, therefore, it may be found that the computed values of K_{MHL} vary considerably between successive iterations although values for the metal stability constants have remained stationary.

The absence of complexes higher than ML (or ML_2, etc.) is generally revealed by the production of negative values for β_2 (or β_3, etc.). In such cases it is expedient to repeat the calculations with the appropriate lower value for N, the maximum co-ordination number: the simplification is shown to be justified if there is a concomitant reduction in the computed root-mean-square deviation, d. Such a decision is confirmed (and can indeed be anticipated) by plotting the formation curve ($\bar{n}$ against $pL = -\log_{10}[L]$, a procedure which is facilitated by arranging for values of $\bar{n}$ and pL to be printed out during the course of the programme.

In computations of results from neutralisation data of polybasic acids, alone or in the presence of metals, it is obvious that every observation will not be of equal weight. In the range between the buffer regions (usually at integral a-values) the value of pH may change very rapidly for small changes in the volume of titrant added (see Fig.). From the form of equation (13) the greatest percentage errors in individual terms of the equation occur when $\bar{n}$ approaches an integral value. For this reason it has always been customary to make a judicious selection from experimental data before starting any calculations. It would clearly be desirable, and relatively easy, to include in the computor programme some provision for weighting experimental observations according to some pre-arranged assessment of their precision. We have not solved this problem to our satisfaction. An independent approach to the whole problem of computing stability constants has been described recently by Sullivan, Rydberg, and Miller who discuss several possible ways of weighting the experimental data.[6]

Discussion

The annexed Table summarises values for the acid dissociation constants for the homologous complexones (II; X = O, n = 2 and 3) and values for the metal stability constants K_{MY}, $K_{MHY} = [MHY]/[M][HY]$, and $K^H_{MHY} = [MHY]/[H][MY]$.

Increase in the size of two chelate rings of MY^{2-} from five- to six-membered has produced the expected decrease in stability,[3] but the order $Hg \gg Cd \gg Ca > Sr > Mg > Ba$ has now become $Hg \gg Cd > Zn \gg Ca > Mg > Sr > Ba$, *i.e.*, the smaller magnesium ion is now favoured. A similar effect is seen in the order of values for K^M_{MHY}. It is noteworthy that whole-ring expansion lowers the stability of alkaline-earth complexes, MY^{2-}, by 3·5—5·2 log units (4·8—7·1 kcal. $mole^{-1}$); those of cadmium and zinc are only lowered by 1·5—2·0 log units (2·0—2·7 kcal. $mole^{-1}$). The stability of the calcium complex has been decreased less than that of the strontium complex so that the complexone (II; X = O, n = 3) is less selective for strontium as well as being a far less powerful chelating agent.

Of other complexones of similar structure and proton affinity the closest comparison can be made to the tetradentate methoxyethyliminodiacetic acid, $MeO{\cdot}C_2H_4{\cdot}N(CH_2{\cdot}CO_2H)_2$ (cf. Table of stability constants). Although data for the alkaline earths are restricted to 1 : 1 complexes, values of log K_2 ranging from 1·5 to 2·0 would not be unreasonable: these would lead to values of log β_2 of a similar order to those found for complexes of (II;

[6] Sullivan, Rydberg, and Miller, *Acta Chem. Scand.*, 1959, **13**, 2023.

X = O, $n = 3$). The 1 : 2 complexes formed by methoxyethyliminodiacetic acid with zinc and cadmium are comparable in stability with those of (II; X = O, $n = 3$) but the increased stability associated with its five-membered rings does not compensate for the smaller " chelate effect " [7] associated with complex formation by a tetradentate ligand in comparison with the much larger decrease in free energy found with the potentially

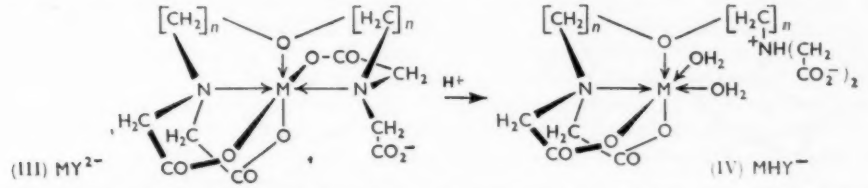
Stability constants of metal complexes of acids (II; X = O, $n = 2$ and 3). *Valid for* 20° *and* $\mu = 0{\cdot}1$M-KCl.

		Mg	Ca	Sr	Ba	Zn	Cd	Hg
pK values for H_4Y								
$n = 2$			1·8 [a]					
$n = 3$			2·0 [b]					
			2·1 [c]					
pK values for H_3Y^-								
$n = 2$			2·76					
$n = 3$			2·74					
			2·7					
pK values for H_2Y^{2-}								
$n = 2$			8·84					
$n = 3$			9·64					
			9·67					
pK values for HY^{3-}								
$n = 2$			9·47					
$n = 3$			10·14					
			10·17					
$\log K_{MY}$	$n = 2$	8·32	10·0	9·34	8·15	—	16·27	23·09
	$n = 3$	4·8	5·38	4·15	3·77	13·53	14·22	21·67
			5·39 [c]				14·29 [d]	
$\log K^{M}_{MHY}$	$n = 2$	3·8	4·9	4·6	4·0	—	9·90	16·14
	$n = 3$	3·92	4·04	3·06	2·69	9·19	8·20	15·0
			4·0 [c]					
$\log K^{H}_{MHY}$	$n = 2$	4·95	4·4	4·7	5·3	—	3·1	2·5
	$n = 3$	9·3	8·9	9·1	9·2	5·9	4·2	3·6
			8·8 [c]					
Cf. methoxyethyliminodiacetic acid								
$\log K_{ML}$		3·31	4·53	3·84	3·56	8·43	7·53	5·94
$\log \beta_2$		—	—	—	—	12·85	13·18	10·03

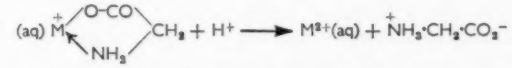
[a] All data for acid (II; X = O, $n = 2$) are from Schwarzenbach, Senn, and Anderegg.[3] [b] Data for acid (II; X = O, $n = 3$) are from the present paper. [c] Cf. ref. 2. [d] Values obtained by using the mercury electrode, $\mu = 0{\cdot}1$M-$NaNO_3$. [e] For methoxyethyliminodiacetic acid, $MeO{\cdot}C_2H_4{\cdot}N(CH_2{\cdot}CO_2H)_2$, p$K$ of $H_2L = 2{\cdot}1$ and of $HL^- = 8{\cdot}91$.

hexadentate ligand (II). The abnormally low stability of the mercury complex of methoxyethyliminodiacetic acid ($\log \beta_2 = 10{\cdot}03$) compared with that of the complexone (II; X = O, $n = 3$), *viz.*, 21·67, is very difficult to understand.

Values of K^{H}_{MHY} in the Table show that increase in the chain length of the ligand causes an increase in the basicity of the 1 : 1 complex MY^{2-}. With the alkaline earths the average value of $4{\cdot}8 \pm 0{\cdot}4$ ($n = 2$) increases to $9{\cdot}1 \pm 0{\cdot}2$ for the higher homologue ($n = 3$). If the proton in MHY^- is attached to a nitrogen atom (rather than to an oxygen atom of a carboxylate ion) this will become incapable of co-ordinating to a metal and two chelate rings must be broken in the transition $H^+ + MY^{2-} \longrightarrow MHY^-$, (III ⟶ IV).



The protonation of MY^{2-} to MHY^- may be compared with the protonation of a 1 : 1 complex of a bivalent ion with an amino-acid to form the zwitterion $HZ^{\pm}$, *viz.*:



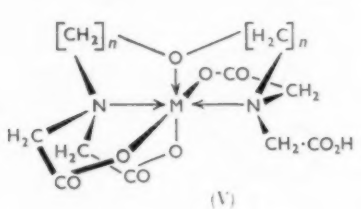
Ceteris paribus, the change in free energy (III ⟶ IV) measured by $\log K^{H}_{MHY}$ should be comparable to that in the latter reaction as measured by $pK_{HZ^{\pm}} - \log K_1$ (metal glycine). For calcium and glycine $\log K_1 \approx 1{\cdot}2$, whence $\log K^{H}_{CaHY} = 10{\cdot}2 - 1{\cdot}2 =$

[7] Schwarzenbach, *Helv. Chim. Acta*, 1952, **35**, 2344.

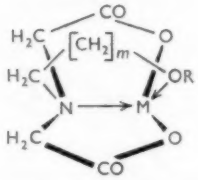
9·0 (found 8·9) and log $K^{H}_{ZnHY} = 10·2 - 5 = 5·2$ (found 5·9). Although the agreement is certainly fortuitous, the chelate effect [7] must favour the formation of MY^{2-} from MHY^{-} and the value of K^{H}_{MHY} should therefore become larger as the size of the chelate ring increases from five- to six-membered. This is found experimentally (Table).

The structure (V) for MHY^{-} is inadmissible, for log K^{H}_{MHY} would not then be much greater than ~2·2, the value for the dissociation of the first proton from glycine.[8] If the proton is assumed to be attached to a nitrogen atom in the species MHY^{-} derived from the acid (II; X = O, $n = 3$), the free energy of formation of a complex (IV; $n = 3$) from HY^{3-} and M^{2+} (which is measured by the stability constant K^{M}_{MHY}) may be compared with the values for 1 : 1 complexes of the same metals with the anion, Y^{2-}, of methoxyethyliminodiacetic acid. Naturally the values will be somewhat lower since a six-membered ring has replaced a five-membered one. The agreement is good for the alkaline earths Ca, Sr, and Ba, but with the more strongly polarising ions of magnesium, zinc, and cadmium the protonated complexes formed by the acid (II; X = O, $n = 3$) are the stronger by 0·6—0·8 log unit: the difference for the mercury complex is again anomalously high (~9 log units) and raises some doubts concerning the validity of the stability data for the mercury complexes of methoxyethyliminodiacetic acid.

The Table of stability constants shows that the protonated complex, MHY^{-}, of zinc is more stable than that of cadmium, although the 1 : 1 complex, MY^{2-}, of cadmium is more stable than that of zinc. This accounts for the crossing of the titration curves shown in the Figure. A similar anomaly is shown by complexes of methoxyethyliminodiacetic acid (Table) where the 1 : 1 complex with zinc is more stable than that of cadmium although its overall stability is less. The same behaviour characterises a number of other tetradentate ligands.[8] With ethylenediamine K_1 and K_2 are greater for zinc than for cadmium, but the third molecule of ligand is attached more firmly to cadmium than to zinc.[8] These peculiarities may be connected with the tendency of the smaller zinc ion to favour a tetrahedral structure. Thus a tetrahedral structure (as VI) may result with the tetradentate ligands formed by the ion HY^{3-} of the complexone (II; X = O, $n = 3$) when forming the protonated complex MHY^{-}, or with the anion, Y^{2-}, of methoxyethyliminodiacetic acid or its analogues. Here the stability order will be Zn > Cd. With the hexadentate ion, Y^{4-}, from an acid (II; X = O, $n = 3$), or with two molecules of methoxyethyliminodiacetic acid (or with three molecules of ethylenediamine) octahedral co-ordination will be easier for the larger ion (as III), so that stabilities will be in the order Cd > Zn.



(V)



(VI) $m = 1$, R = Me
$m = 2$, R = $C_3H_6{\cdot}NH(CH_2{\cdot}CO_2^{-})_2$

The stability ($K_{HgY} = 10^{21·64}$) of the mercury complex of acid (II; X = O, $n = 3$) ($pK_{HY} = 10·23$) which has a chain of seven atoms ($-C_3H_6{\cdot}O{\cdot}C_3H_6-$) between the two linearly co-ordinated nitrogen atoms would not be expected to differ greatly from that of an analogue of acid (I; $n = 7$) of similar proton affinity, provided the oxygen atom did not participate in co-ordination. From the values $pK_{HY^{-}} = 10·7$ and log $K_{MY} = 21·6$ interpolated from data [2] for the complexones (I; $n = 6$ and 8), a value of log $K_{HgY} < 21·6$ would be predicted for a ligand of $pK_{HY} = 10·23$ that forms a ten-membered chelate

[8] "Tables of Stability Constants," *Chem. Soc. Spec. Publ.*, No. 7, Part I, 1957.

ring. The experimental value for the mercury complex of (II; X = O, $n = 3$) is $10^{21\cdot7}$, which shows that the oxygen atom does co-ordinate to mercury though far less effectively than sulphur or nitrogen does, as would be expected from the character of this element.[1,2]

INORGANIC CHEMISTRY LABORATORY,
THE UNIVERSITY, OXFORD.

[*Received, August 30th*, 1960.]

---

385. *The Nature of the Porter–Silber Reaction.*

By D. H. R. BARTON, T. C. MCMORRIS, and R. SEGOVIA.

The Porter–Silber reaction has been shown to involve acid-catalysed rearrangement of the adrenocortical side chain to a 20,21-glyoxal grouping followed by formation of the 21-(mono)phenylhydrazone. A compound containing the typical Porter–Silber chromophore has been isolated in crystalline form and shown to undergo a reversible mutarotation at room temperature. The reason for this mutarotation has been investigated and its solvent-dependence briefly studied.

TREATMENT of steroids containing the adrenocortical side chain (as in I) with phenylhydrazine in diluted sulphuric acid produces a characteristic absorption at about 410 mμ.[1] This procedure has become an important method for the detection and determination of adrenocortical steroids in biological materials and is generally known as the Porter–Silber reaction.[1] To our knowledge there has been no definitive work on the constitution of the Porter–Silber chromophore although Walsen and Schlunk [2] recently proposed that it is as in (VI). Since the significance of the reaction should not be judged without a knowledge of the structures we examined the matter further. The present paper shows that the Porter–Silber chromophore is represented by the partial structure (III).

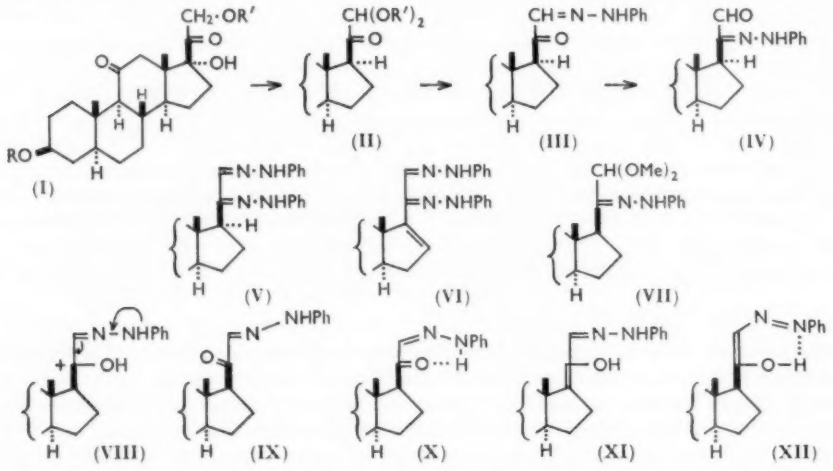
It seemed to us *a priori* that the chromophore would be derived from the glyoxal grouping (as II; R′ = H) itself formed by the type of rearrangement of the adrenocortical side chain under acid conditions observed by Mattox.[3] To test this hypothesis 21-acetoxy-3β,17α-dihydroxy-5α-pregnane-11,20-dione (I; R = H, R′ = Ac), an intermediate in the synthesis of the adrenocortical hormones,[4] was treated with methanolic hydrogen chloride [3] to give 3β-hydroxy-21,21-dimethoxy-5α-pregnane-11,20-dione (II; R = OH, R′ = Me). When kept at room temperature under the conditions of the Porter–Silber reaction [1] this acetal afforded 3β-hydroxy-11,20,21-trioxo-5α-pregnane 21-phenylhydrazone (III; R = H), characterised as its 3-acetate. The phenylhydrazone (III; R = H), on dissolution in diluted sulphuric acid, showed the characteristic maximum of the Porter–Silber chromophore. More importantly, when the Porter–Silber reaction was applied directly to the acetate (I; R = H, R′ = Ac) and the product was acetylated and filtered through alumina the same acetate phenylhydrazone (III; R = Ac) was obtained. The Porter–Silber colour developed at least thirty times faster when the test was applied to the acetal (II; R = H, R′ = Me) than when it was applied to the intact adrenocortical side chain as in (I; R = H, R′ = Ac).

In principle the monophenylhydrazone obtained in these reactions could be a derivative of the 21-aldehyde or of the 20-ketone (as IV). For comparison, pyruvaldehyde phenylhydrazone [5] was shown to have a band at 393 mμ in diluted sulphuric acid, comparable with that at 408 mμ shown by the 21-hydrazone (III; R = H). More significant was the following experiment. When the dimethyl acetal (II; R = H, R′ = Me) was treated

[1] Porter and Silber, *J. Biol. Chem.*, 1950, **185**, 201; 1954, **210**, 923.
[2] Walsen and Schlunk, *Experientia*, 1959, **15**, 71.
[3] Mattox, *J. Amer. Chem. Soc.*, 1952, **74**, 4340.
[4] Evans, Hamlet, Hunt, Jones, Long, Oughton, Stephenson, Walker, and Wilson, *J.*, 1956, 4356.
[5] Reynolds and van Allan, *Org. Synth.*, 1952, **32**, 84.

XUM

with phenylhydrazine hydrochloride and sodium acetate in aqueous methanol at room temperature, it afforded a yellow precipitate having 280 mμ (ε 11,400) indicative of the saturated phenylhydrazone chromophore (as VII). On acetylation with pyridine–acetic anhydride and working up in the usual way there resulted the monophenylhydrazone (IV;



R = Ac) having $\lambda_{max.}$ 340 mμ (ε 15,800). The Porter–Silber chromophore (III; R = Ac) exhibited a comparable maximum in ethanol at 350 mμ but of much greater intensity (ε 27,500). In addition the two compounds (III; R = Ac) and (IV; R = Ac) were different in every other physical property.

When warmed with phenylhydrazine hydrochloride and sodium acetate in aqueous ethanol the dimethyl acetal (II; R = H, R′ = Me) gave the osazone (V; R = H). This was also obtained from the 21-hydrazone (III; R = H) in the same conditions.

It appears that in the strongly acidic conditions of the Porter–Silber reaction protonation of the chromophore (as III) to give a chromophore (as VIII), responsible for the characteristic maximum, prevents further reaction with phenylhydrazine. In consequence an osazone is not, in fact, formed under the normal conditions of the Porter–Silber reaction.

The acetate phenylhydrazone (III; R = Ac) showed a large negative rotation ($[\alpha]_D$ −150°) in CCl_4 which changed in 6 hr. to a positive value (+125°). Removal of the solvent and crystallisation from methanol gave back the original material with the large negative rotation. The solvent-dependence of this phenomenon was then examined with the results summarised in the Table. All solutions were kept in the dark at room temperature (23° ± 3°).

Solvent	Concn. (*c*)	Initial $[\alpha]_D$	$[\alpha]_D$ after various times (in parentheses)
CCl_4	0·56	−150°	+125° (6 hr.), +141° (3 days)
$CHCl_3$	0·79	−128	+38 (3 hr.), +39 (2 days)
,,	0·53	−128	+38 (2 hr.)
,,	1·10	−127	+30 (6 hr.)
C_6H_6	0·75	−192	−29° (11 days)
Tetrahydrofuran	0·55	−126	−120 (18 hr.), −113 (24 days)
EtOAc	0·89	−172	−134 (24 hr.), −113 (15 days)
Pyridine	0·85	−206	−206 (24 hr.)
MeOH	0·96	−227	−201 (24 hr.)

The simplest interpretation of these results is that a solvent-dependent equilibrium is set up between the *trans*- (IX) and the *cis*-configuration (X) for the monophenylhydrazone. In well-solvating solvents the *trans*-isomer is stabilised whereas in poorly

solvating solvents " internal solvation " is favoured through formation of a strong (O–N–H) hydrogen bond. The evidence for this is briefly as follows. Although the mutarotated carbon tetrachloride solution showed little change in its ultraviolet absorption spectrum it gave a significantly different infrared spectrum. The initial solution showed the usual bands for the 3β-acetate and 11-ketone as well as a sharply defined N–H band at 3240 cm.$^{-1}$. The 20-carbonyl group gave (in CCl_4) a band at 1660 cm.$^{-1}$ as would be expected for an αβ-unsaturated β-hydrazino-ketone chromophore.[6] After mutarotation the NH band had vanished and the 20-ketone band had largely disappeared. This result appears to exclude enolisation to a system such as (XI), since the NH band would then be retained. Besides the hydrogen-bonded ketone formula (X), one must also consider the enolic form (XII). These are distinct molecular species whose relative proportions are known to be solvent-dependent.[7] However, it seems most improbable that an intramolecular proton-transfer from nitrogen to oxygen, (X) ⟶ (XII), could be so strongly activated at room temperature as to require several hours for completion.[8] We do not consider, therefore, that the rearrangement of (X) to (XII) can represent the process under investigation. The mutarotation appears to be best explained by a rearrangement of the *trans*- (IX) to the *cis*-hydrazone (X), which can exist as (X) or as (XII) or as a mixture of the two (see above).

Experimental

M. p.s were taken on the Kofler block. Ultraviolet absorption spectra were, unless specified to the contrary, determined for ethereal solutions with the Unicam S.P. 500 spectrophotometer. Infrared spectra were determined for Nujol mulls. Light petroleum refers to the fraction of b. p. 60—80°. $[\alpha]_D$ are for $CHCl_3$ solutions unless indicated otherwise. The expression " diluted sulphuric acid " refers to a solution made 31 : 19 (v/v) sulphuric acid–water.

3β-*Hydroxy*-21,21-*dimethoxy*-5α-*pregnane*-11,20-*dione*.—This *compound* (II; R = H; R′ = Me) was prepared from 21-acetoxy-3β,17α-dihydroxy-5α-pregnane-11,20-dione by the general procedure of Mattox.[3] Recrystallised from methanol it had m. p. 150—151°, $[\alpha]_D$ +109° (*c* 1·47) (Found: C, 70·35; H, 9·2; OMe, 17·8. $C_{23}H_{36}O_5$ requires C, 70·4; H, 9·2; OMe, 15·8%).

3β-*Hydroxy*-11,20,21-*trioxo*-5α-*pregnane* 21-*Phenylhydrazone*.—The preceding acetal (50 mg.) in ethanol (2·5 ml.) was added to a 1% solution of phenylhydrazine hydrochloride in diluted sulphuric acid (5 ml.). The resulting solution, which rapidly became orange-coloured, was left at room temperature for 30 min. Dilution with water gave a yellow precipitate (40 mg.) which, on crystallisation from methanol, had m. p. 182—185°. Analysis showed solvation by methanol. Further crystallisation from acetic acid then gave the 21-*phenylhydrazone*, m. p. 213—215°, $[\alpha]_D$ −158° (*c* 1·03), +8° (after 24 hr), $\lambda_{max.}$ 238, 290, 296, and 350 mμ (ε 13,900, 4700, 5300, and 23,700 respectively), $\lambda_{max.}$ [in diluted sulphuric acid–ethanol (2 : 1)] 253, 408 mμ (ε 6600 and 23,800 respectively), $\nu_{max.}$ 1695 (11-C=O), 1631 (conjugated 20-C=O) and 1600 (aromatic C=C) cm.$^{-1}$ (Found: C, 74·0; H, 8·0; N, 7·05. $C_{27}H_{36}N_2O_3$ requires C, 74·3; H, 8·3; N, 6·4%).

The phenylhydrazone was treated with pyridine–acetic anhydride overnight at room temperature, to give the 3β-*acetate*. Recrystallised from methanol this had m. p. 144—146°; recrystallised from acetic acid it had m. p. 139—141°, $[\alpha]_D$ −128° (*c* 0·53), +38° (after 2 hr.), $\lambda_{max.}$ 238, 290, 298, and 350 mμ (ε 14,400, 5500, 5800, and 27,500 respectively), $\nu_{max.}$ 1720 (OAc and acetic acid carboxyl), 1701 (11-C=O), 1633 (conjugated 20-C=O) and 1603 (aromatic C=C) cm.$^{-1}$ (Found: C, 68·75; H, 7·75. $C_{29}H_{38}N_2O_4,CH_2{\cdot}CO_2H$ requires C, 69·1; H, 7·85%). Titration with 0·5N-sodium hydroxide in ethanol confirmed the presence of 1 mol. of acetic acid.

[6] See, *inter al.*, Cromwell, Miller, Johnson, Frank, and Wallace, *J. Amer. Chem. Soc.*, 1949, **71**, 3337; Hadži, *J.*, 1956, 2143; Weinstein and Wyman, *J. Org. Chem.*, 1958, **23**, 1618; Stachel, *Chem. Ber.*, 1960, **93**, 1059.

[7] Burawoy, Salem, and Thompson, *J.*, 1952, 4793; Burawoy, Cais, Chamberlain, Liversedge, and Thompson, *J.*, 1955, 3721, 3727.

[8] See, for example, Swain and Labes, *J. Amer. Chem. Soc.*, 1957, **79**, 1084, and references there cited.

XUM

The 3β-acetate phenylhydrazone (III; R = Ac) (30 mg.) in ethanol (0·8 ml.) and 15% aqueous potassium carbonate (0·2 ml.) was shaken (suspension) for 48 hr. The ethanol was removed *in vacuo* and the residue extracted with chloroform. Crystallisation from methanol and then from glacial acetic acid gave the 3β-hydroxy-phenylhydrazone (III; R = H), identified by m. p., mixed m. p., and ultraviolet and infrared spectra. It showed $[\alpha]_D$ −157° (*c* 0·78), +8° (after 24 hr.).

The 3β-acetate phenylhydrazone (III; R = Ac) (10 mg.) was allowed to mutarotate at room temperature in CCl_4 from $[\alpha]_D$ −150° to $[\alpha]_D$ +125° (6 hr.). The solvent was removed *in vacuo* and the residue crystallised once from methanol to give back the original acetate, identified by m. p., mixed m. p., and rotation. In a second experiment the 3β-acetate phenyl hydrazone (91 mg.), which had mutarotated to $[\alpha]_D$ +129°, was worked up to give starting material in three crops (54 + 23 + 12 mg.). The identity of each crop was checked by m. p., mixed m. p., rotation, and mutarotation.

A portion (69 mg.) of the product (368 mg.) from a Porter–Silber reaction with 21-acetoxy-3β,17α-dihydroxy-5α-pregnane-11,20-dione (399 mg.) was treated at room temperature with pyridine–acetic anhydride for 18 hr. The derived acetate was filtered in benzene–light petroleum (1 : 1) through alumina (Grade V) and then crystallised from methanol, to furnish the acetate phenylhydrazone (III; R = Ac) characterised as above. The identity was established by m. p., mixed m. p., and ultraviolet and infrared spectra.

Pyruvaldehyde Phenylhydrazone.—This compound [5] had $\lambda_{max.}$ 237, 295, and 344 mμ (ε 12,700, 4600, and 21,600 respectively), $\lambda_{max.}$ [in diluted sulphuric acid–ethanol (2 : 1)] 393 mμ (ε 25,400), $\nu_{max.}$ 1644 (conjugated C=O) and 1600 (aromatic C=C) cm.$^{-1}$.

3β-Hydroxy-11,20,21-trioxo-5α-pregnane Bisphenylhydrazone.—3β-Hydroxy-21,21-dimethoxy-5α-pregnane-11,20-dione (100 mg.) with phenylhydrazine hydrochloride (500 mg.) and hydrated sodium acetate (500 mg.) in water (4 ml.) was warmed with the minimum of ethanol to give a solution and then refluxed for 15 min. The yellow crystalline precipitate which separated (110 mg.) had m. p. 243—250°. Recrystallisation from chloroform–methanol afforded the desired *phenylosazone* (V; R = H), m. p. 250—254°, $[\alpha]_D$ −72° (*c* 1·00), $\lambda_{max.}$ 257, 310, and 395 mμ (ε 18,600, 11,000, and 17,700 respectively), $\lambda_{max.}$ [in diluted sulphuric acid–ethanol (2 : 1)] 260 and 416 mμ (ε 10,900 and 25,400 respectively), $\nu_{max.}$ 1695 (11-C=O) and 1592 (aromatic C=C) cm.$^{-1}$ (Found: C, 74·7; H, 7·95; N, 10·15. $C_{33}H_{42}N_4O_2$ requires C, 75·25; H, 8·05; N, 10·65%).

The osazone was also obtained by refluxing 3β-hydroxy-11,20,21-trioxo-5α-pregnane 21-phenylhydrazone (84 mg.) with phenylhydrazine hydrochloride (200 mg.) and hydrated sodium acetate (200 mg.) in the minimum of aqueous ethanol. After 4 hours' refluxing the crystalline osazone was filtered off (70 mg.) and identified by m. p. and mixed m. p.

3β-Acetoxy-11,20,21-trioxo-5α-pregnane 20-Phenylhydrazone (IV; R = Ac).—3β-Hydroxy-21,21-dimethoxy-5α-pregnane-11,20-dione (180 mg.) in methanol (10 ml.) was added to a solution of phenylhydrazine hydrochloride (90 mg.) and hydrated sodium acetate (90 mg.) in water (5 ml.), and the solution left for 2 hr. at room temperature. Dilution with water gave a yellow precipitate (140 mg.), $\lambda_{max.}$ 280 mμ (ε 11,400), indicative of the saturated phenylhydrazone (VII; R = H). The precipitate was treated with pyridine (1·0 ml.) and acetic anhydride (0·5 ml.) overnight at room temperature. The product was chromatographed over alumina (Grade V; 30 g.). Elution with benzene–light petroleum (1 : 1) gave the desired *21-aldehyde 20-phenylhydrazone* (IV; R = Ac) (60 mg.). Recrystallised from chloroform–methanol this had m. p. 221—223°, $[\alpha]_D$ +24° (*c* 1·02), $\lambda_{max.}$ 236 and 340 mμ (ε 11,000 and 15,800 respectively), $\lambda_{infl.}$ 298 mμ (ε 5100), $\nu_{max.}$ 1720 (OAc), 1698 (11-C=O), 1645 (conjugated 21-CHO) and 1597 (aromatic C=C) cm.$^{-1}$ (Found: C, 72·65; H, 8·1; N, 6·1. $C_{29}H_{38}N_2O_4$ requires C, 72·75; H, 8·0; N, 5·85%). The infrared spectrum of this compound in the "finger-print" region was very different from that of the isomer (III; R = Ac).

Comparison of Rate of Development of Porter–Silber Colour.—The rates of chromogen formation from 21-acetoxy-3β,17α-dihydroxy- and from 3β-hydroxy-21,21-dimethoxy-5α-pregnane-11,20-dione were compared as follows. The compound (10 mg.) in ethanol (2·5 ml.) was mixed with 1% phenylhydrazine hydrochloride solution in diluted sulphuric acid (5 ml.) until homogeneous at room temperature. At definite intervals aliquot parts (0·1 ml.) were removed, the appropriate amount of diluted sulphuric acid was added, and the absorption intensity at 408 mμ determined. The appropriate control runs were made at the same time. The Table shows the resulting optical densities at 408 mμ in arbitrary units.

XUM

Time (hr.)	0·33	1	1·5	2·5	3·5
17α-OH, 21β-OAc	0·01	0·04	0·06	0·10	0·13
17α-H, 21,21-$(OMe)_2$	0·33	0·38	0·37	0·38	0·37

We thank the Government Grants Committee of the Royal Society and Imperial Chemical Industries Limited for financial assistance. One of us (T. C. McM.) acknowledges support from the Commonwealth Universities Committee, another (R. S.) a Fellowship from the Comisaría Protección Escolar (Spain). The steroids used in this work were kindly provided by Messrs. Glaxo Laboratories Ltd. The interest of Dr. M. M. Pechet of Harvard University is gratefully acknowledged.

Imperial College of Science and Technology,
S. Kensington, London, S.W.7. [*Received, September 29th*, 1960.]

---

386. *The Vapour Pressure of Plutonium Tetrafluoride.*

By C. J. Mandleberg and D. Davies.

The vapour pressure of plutonium tetrafluoride has been measured by Knudsen's effusion method, as modified by Phipps *et al.* Between 700° and 1200° c, the vapour pressure can be represented by $\log_{10} p$ (mm. Hg) = $5{\cdot}58 - 10{,}040/T$; above 1200° a more volatile species occurs, whose vapour pressure can be represented by $\log_{10} p$ (mm. Hg) = $36{\cdot}1 - 54{,}180/T$. Above 1200° the residue remaining in the effusion pot is plutonium trifluoride and it is tentatively suggested that the species effusing above 1200° is the pentafluoride.

Phipps *et al.*[1] describe an elegant method of determining the vapour pressure of radioactive substances in which they use a modification of the classical Knudsen effusion method. In the latter, vapour effuses for a definite time from an oven maintained at a constant temperature, and the mass of the material which has effused is determined by weighing the oven before and after the experiment. The vapour pressure at the temperature is calculated from Knudsen's formula.

The modification enables a known fraction of the effusing material to be collected on a counting tray. The total amount effused is determined by normal counting of the activity collected during the time of the experiment. The vapour pressures of plutonium trifluoride, trichloride, tribromide, and dioxide, and metallic americium were measured by Phipps, and other workers have measured the vapour pressures of other compounds, for instance, beryllium oxide,[2] by similar techniques.

The method is fully described in the literature and only those points which directly concerned the design of our apparatus will be discussed here.

The spatial distribution of molecules which flow into an evacuated space through a small hole in an infinitely thin boundary was discussed by Knudsen,[3] and Clausing[4] has extended the treatment to a finite boundary where the hole resembles a short tube. The spatial distribution of the molecules does not affect the total number effusing from such a hole in unit time, or the validity of the classical Knudsen effusion method. Clausing shows that, where the length of the hole L is twice the radius r, then, at an angular displacement of 5°, the number of molecules entering into an element of unit volume is 0·9444 of that predicted by the cosine law. Although there is disagreement (cf. Mayer[5]) about the magnitude of this departure from the cosine law, such departure will be a minimum when

[1] Phipps, Sears, Seifert, and Simpson, NNES XIVb paper 6.1a; Phipps, Sears, and Simpson, *ibid.*, 6.1b; Erway and Simpson, A.E.C.D. 2733 (1948).
[2] Erway and Seifert, M.D.D.C. 9030 (1946).
[3] Knudsen, *Ann. Phys.*, 1909, **28**, 75; 1909, **29**, 179.
[4] Clausing, *Z. Phys.*, 1930, **66**, 471.
[5] Mayer, *Z. Phys.*, 1928, **52**, 235; 1929, **58**, 373.

XUM

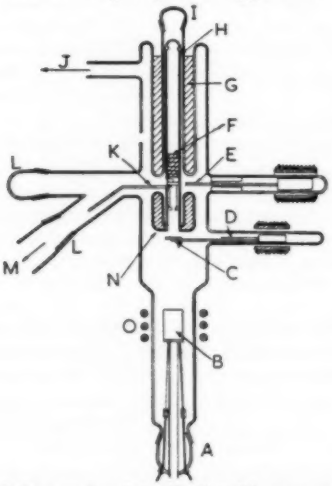
(*a*) the thickness of the boundary is not large compared with the diameter of the orifice and (*b*) the diameter of the collimator subtends a small angle at the orifice.

Since the validity of the cosine law is assumed in this work, conditions (*a*) and (*b*) were of prime importance in designing the apparatus. In every case $L < r/4$ and the angle subtended by the collimator was about 2°. Thus departure from the cosine law could be safely assumed to be negligible.

Experimental

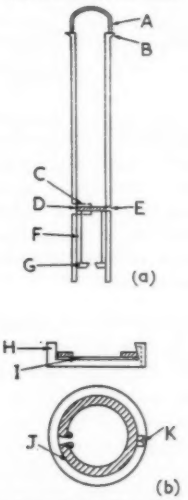
The apparatus (Fig. 1) was used for runs II—V; run I was made in one differing slightly from this design. Also in run I, the effusion oven was of nickel; tantalum ovens were used for

Fig. 1. *Vapour-pressure apparatus.*



A, B50 *Cone and socket.* B, *Crucible surrounded by radiation shield.* C, *Vapour cut-off.* D, *Glass guides for ejector and vapour solenoids cut-off.* E, *Cassette ejector.* F, *Cassettes.* G, *Liquid oxygen for cooling cassettes.* H, *Cassette holder.* I, B40 *Cone and socket.* J, *To vacuum line.* K, *Aluminium cassette guide.* L, B34 *Cone and socket.* M, *To cassette collector.* N, *End of oxygen trap extended inwards to form a ledge to support cassette holder.* O, RF *Coil.*

Fig. 2. (a) *Cross-section of cassette holder.*
(b) *Detail of cassette.*



A, *Handle for lowering holder into position.* B, *Ridge to prevent side-play.* C, *Slot to allow discharge of cassettes.* D, *Cassette in position.* E, *Hole to admit ejector rod.* F, *Glass sleeve to hold cassette in position.* G, *Collimator.* (N.B. *Cassettes are inserted when loaded in the holder*). H, *Aluminium holder.* I, *Platinum collecting tray.* J, *Metal circlip to hold platinum tray.* K, *V-Shaped cut-away to accelerate pumping-out.*

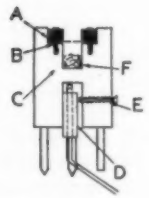


Fig. 3. *Cross-section of tantalum crucible (enlarged plan).*

A, *Collar clamping foil in position.* B, 2/1000″ *Foil with orifice pierced in centre.* C, *Tantalum crucible* (7/8″ *diam.*). D, *Thermocouple secured in twin-bore silica tubing.* E, *Tantalum grub screw.* F, PuF_4 *charge.*

the others. In the final form the apparatus consisted of a glass container in which the pressure could be reduced to *ca.* 10^{-6} mm. Hg. The tube was as narrow as possible in the region of the effusion pot to achieve the best linkage between it and the radiofrequency induction coil. Above this, the cassette magazine (Fig. 2a) was accommodated in a jacket holding liquid air. A shield could be moved across by means of an energised coil to control the times during which

the targets were exposed to the effusing vapour. A second coil enabled the lowest cassette holding an exposed target to be pushed out so that it fell down a sloping platform into a removable tube. When the pusher was retracted, the column of cassettes fell under gravity so that the lowest took the place of that one which had been ejected. The collimator was a circular knife-edged hole accurately ground in a glass disc, and fused on to the bottom of the magazine. The magazine was removable through the top of the apparatus.

The targets were discs of platinum, 2 cm. in diameter and 5/1000″ thick, held in aluminium cassettes, 0·5 cm. thick, by means of circlips (Fig. 2*b*). The maximum number which could safely be held in the magazine was 25, but for various reasons as many as this were never employed at one time. Before use, the targets were checked for alpha-contamination in a low-background scintillation-counter, and then refluxed for some hours in carbon tetrachloride to remove grease, this being necessary in order to provide a surface with a high accommodation coefficient and thus to ensure that the maximum incident molecules adhered to the target. For the same reason the targets were surrounded by an outer vessel containing liquid air, since the accommodation coefficient is considerably increased by cooling (cf. refs. 6 and 7).

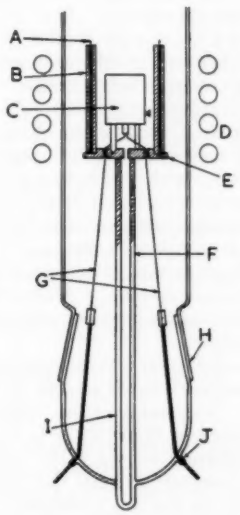


FIG. 4. *Cross-section of crucible arrangement.*

□ *Glass.* ▨ *Silica.*

A, *Platinum foil radiation-shield.* B, *Silica sleeve to support shield.* C, *Tantalum crucible.* D, RF *coils.* E, *Silica platform.* F, *Graded silica seal.* G, *Thermocouple leads.* H, B50 *Pyrex cone and socket.* I, *Glass supporting pillar.* J, *Metal–glass seal.*

The apparatus was evacuated by a standard rotary and diffusion pump system.

Each furnace pot (Fig. 3) holding tetrafluoride was $\frac{7}{8}$″ in diameter. The tantalum foil in which the effusion orifice was pierced rested on the " step " and was secured by a tantalum collar held by four tantalum grub screws. During the initial stages of the heating the tantalum appeared to sinter slightly (perhaps owing to traces of absorbed oxygen); the collar and foil became firmly attached to the pot so that it is not thought that an appreciable quantity of vapour could effuse except through the orifice. The pot had three tantalum legs, two ground to a point, the other flat so that the vessel could be accurately located by a V-section hole and groove on the flat silica supporting platform (cf. Erway and Simpson [1]). A hole drilled in the base of the pot held the platinum–platinum-10% iridium thermocouple, which was insulated by a short length of twin-bore silica tubing and secured by a long tantalum screw. The junction was separated from the charge in the pot by about $\frac{1}{8}$″ of tantalum, and was assumed to be at the same temperature. The thermocouple had previously been calibrated at the melting points of sodium nitrate (306·8°), lithium bromide (535°), sodium bromide (740°), and sodium chloride (803°). At higher temperatures, the temperature equivalent of the E.M.F., which was measured on a " Pye " millivolt potentiometer, was estimated by extrapolation and from the standard tables.

[6] Fraser, " Molecular Rays," Cambridge Univ. Press, 1931.
[7] Cockcroft, *Proc. Roy. Soc.*, 1928, **119**, 293.

XUM

The effusion pot was surrounded by a radiation shield of two concentric silica tubes, $2\frac{1}{2}''$ high with strips of 1/1000″ platinum foil between them. In the earlier experiments with the nickel pots, the inside of the inner tube became somewhat plated with a skin of nickel, and the whole formed a very efficient shield. Various types of resistance heating were first used, but, for all the runs in which measurements are reported, eddy-current heating was employed. The power input was from a $4\frac{1}{2}$ turn copper coil connected to a 7 kw RF generator.

The furnace pot and radiation shield stood upon a silica platform (Fig. 4) which was supported on a hollow silica pillar sealed through a silica-to-Pyrex graded seal to a B40 cone. Into the base of the cone were sealed metal rods to which the thermocouple leads were attached. The B40 cone with the Pyrex-and-silica pillar and platform fitted into a socket at the base of the vapour pressure apparatus itself.

The orifices were pierced in 2/1000″ tantalum foil by Mr. C. F. Wright to whom our thanks are offered. The initial hole was pierced with a sharpened needle on a micro-lathe of special construction, and this was ground out by hand with a specially prepared reamer. The final hole appeared to be a knife-edged channel through the tantalum sheet which remained perfectly plane. The diameters of the holes were measured both by a Zeiss measuring microscope and a projection microscope. Four measurements were made in every case and none deviated by as much as 1% from the mean.

The method of operation was as follows. The grease-free targets, each stamped with a reference number near its edge, were loaded into their cassettes, great care being taken to avoid contaminating the surfaces. They were then placed in the magazine which was lowered into the apparatus, and one disc was pushed out to test the alignment of the pusher. This was all done with plutonium absent, to avoid any alpha-contamination of the clean targets. The pot was then loaded with about 50 mg. of plutonium tetrafluoride. The foil with the orifice hole was attached to the pot and its alignment checked visually. With the furnace pot and the radiation shield on the pillar, and the thermocouple in position, the B40 cone was secured in its socket with Apiezon W vacuum-wax.

The plutonium tetrafluoride had been made by the hydrofluorination of plutonium dioxide by hydrogen fluoride and oxygen at 350°. It contained 23·95% of fluorine (calc. for PuF_4: F, 24·1%) and no phase other than the tetrafluoride could be detected in *X*-ray diffraction photographs.

The apparatus was evacuated for 2—3 days. The insert around the cassette magazine was then filled with liquid air, the target screened by the shutter, and the temperature slowly raised to 550°. Degassing of the heated surfaces occurred but after about an hour the pressure was once more less than 10^{-5} mm. Hg, and the first target was then exposed for a measured time to the effusing vapour. By constant adjustment of the Geneva control of the RF generator it was possible to keep the temperature constant within $\pm 5°$ and usually within $\pm 2°$ as indicated by the thermocouple.

Targets were successively exposed to the effusing vapour at various measured temperatures for appropriate times. The cassettes containing the exposed targets were successively ejected and fell into a tube attached to the apparatus by a cone-and-socket joint. At the end of the run, all the targets were removed from the apparatus before the pot was disturbed and were removed from the glove box, which surrounded the whole apparatus, as quickly as possible to avoid accidental alpha-contamination.

The cassettes themselves were always found to be inactive and the targets were removed from them in the open laboratory. The activity was counted on a scintillation-counter with a low background. During the run, blank trays were pushed out at intervals and these were also counted. This served to check the freedom of the trays from accidental cross-contamination. This was extremely important because, at the lowest temperatures at which vapour pressures were measured, exposure to the effusing beam for upwards of one hour resulted in only 5—50 measured counts per minute being found on a tray. In some of the earlier runs,

TABLE 1. *Nickel pot; diameter of orifice* 0·0073 *cm.*

T	$10^5/T$	p	$\log_{10} p$	T	$10^5/T$	p	$\log_{10} p$
1069°	93·55	$1{\cdot}216 \times 10^{-4}$	$\bar{4}{\cdot}0849$	1245°	80·32	$6{\cdot}576 \times 10^{-3}$	$\bar{3}{\cdot}8180$
1137	87·95	$3{\cdot}842 \times 10^{-4}$	$\bar{4}{\cdot}5845$	1317	75·93	$1{\cdot}630 \times 10^{-2}$	$\bar{2}{\cdot}2122$
1197	83·54	$2{\cdot}113 \times 10^{-3}$	$\bar{3}{\cdot}3249$	1377	72·62	$7{\cdot}631 \times 10^{-2}$	$\bar{2}{\cdot}8826$

In this run an earlier model of the apparatus was used (D 0·784 cm., r 15·1 cm.).

TABLE 2. *Diameter of orifice* 0·0108 *cm.*

T	$10^5/T$	p	$\log_{10} p$
1153°	86·7	$1·067 \times 10^{-3}$	$\bar{3}·0281$
1150	87·0	$1·629 \times 10^{-3}$	$\bar{3}·2121$
1164	85·9	$2·364 \times 10^{-3}$	$\bar{3}·3738$
1208	82·8	$4·923 \times 10^{-4}$	$\bar{4}·4923$
1247	80·2	$3·023 \times 10^{-3}$	$\bar{3}·4804$
1288	77·6	$1·071 \times 10^{-2}$	$\bar{2}·0299$
1336	74·8	$1·628 \times 10^{-2}$	$\bar{2}·2114$
1363	73·2	$3·917 \times 10^{-2}$	$\bar{2}·5930$
1463	68·2	$2·135 \times 10^{-1}$	$\bar{1}·3295$
1492	67·0	$6·607 \times 10^{-1}$	$\bar{1}·8200$
1534	65·2	$1·078 \times 10$	1·0328
1589	62·9	$1·390 \times 10^{2}$	2·1429

TABLE 3. *Diameter of orifice* 0·0234 *cm.*

T	$10^5/T$	p	$\log_{10} p$
968°	103·3	$1·923 \times 10^{-5}$	$\bar{5}·2840$
997	100·3	$9·234 \times 10^{-5}$	$\bar{5}·9654$
1026	97·5	$1·736 \times 10^{-4}$	$\bar{4}·2396$

Run discontinued; pusher jammed.

TABLE 4. *Diameter of orifice* 0·0110 *cm.*

T	$10^5/T$	p	$\log_{10} p$
1014°	98·4	$7·658 \times 10^{-5}$	$\bar{5}·8841$
1028	97·3	$3·196 \times 10^{-5}$	$\bar{5}·5045$
1036	96·5	$1·487 \times 10^{-4}$	$\bar{4}·1722$
1075	93·0	$1·528 \times 10^{-4}$	$\bar{4}·1840$
1099	91·0	$3·538 \times 10^{-4}$	$\bar{4}·5488$
1128	88·6	$3·741 \times 10^{-4}$	$\bar{4}·5729$

Run discontinued; cassette fell off sloping platform on to pot.

TABLE 5. *Diameter of orifice* 0·0106 *cm.*

T	$10^5/T$	p	$\log_{10} p$	T	$10^5/T$	p	$\log_{10} p$
1167°	85·7	$1·888 \times 10^{-4}$	$\bar{4}·2761$	1310°	76·3	$5·578 \times 10^{-3}$	$\bar{3}·7465$
1187	84·2	$5·171 \times 10^{-4}$	$\bar{4}·7136$	1327	75·4	$8·052 \times 10^{-3}$	$\bar{3}·9059$
1225	81·6	$7·914 \times 10^{-4}$	$\bar{4}·8984$	1337	74·8	$1·798 \times 10^{-2}$	$\bar{2}·2547$
1248	80·1	$9·206 \times 10^{-4}$	$\bar{4}·9641$	1351	74·0	$2·937 \times 10^{-2}$	$\bar{2}·4679$
1263	79·2	$1·191 \times 10^{-3}$	$\bar{3}·0760$	1351	74·0	$2·921 \times 10^{-2}$	$\bar{2}·4656$
1279	78·2	$2·297 \times 10^{-3}$	$\bar{3}·3611$	1361	73·5	$3·680 \times 10^{-2}$	$\bar{2}·5658$

before the handling of the targets had been mastered, the blank trays had rather high contamination (*ca.* 100 counts/min.). In the later runs (Tables 1—5) this contamination was very small.

The furnace pot was removed from the apparatus and opened, and the *X*-ray diffraction pattern of the residue examined.

The calculation of the vapour pressure from the activity recorded on the counting trays has been formulated by Phipps *et al.*[1] The expression is:

$$p = \frac{(cT^{\frac{1}{2}})}{t} \frac{(D^2 + 4r^2)}{AD^2} \frac{(M^{\frac{1}{2}})}{239s} \frac{(10^{-6}(2\pi \boldsymbol{R})^{\frac{1}{2}})}{60}$$

where p is the vapour pressure of the material, c the absolute number of disintegrations per minute on a given target, s the specific activity of the plutonium (counts min.$^{-1}$ μg.$^{-1}$), $\boldsymbol{R}$ the molar gas constant, T the oven-temperature (°K), t the time (min.) for which the target is exposed, D the diameter of the collimator (cm.), r the distance (cm.) from the effusion orifice to the collimator, A the area (sq. cm.) of the orifice, and M is the molecular weight of the vapour molecule.

In this apparatus, the diameter of the collimator was 0·550 cm. The distance from the effusion orifice to the collimator differed slightly from run to run, but was typically 15·20 cm. The diameter of the effusion orifice is shown for each run. The calculated vapour pressures are set out in Tables 1—5 (temperatures in °K, pressures in mm. Hg).

DISCUSSION

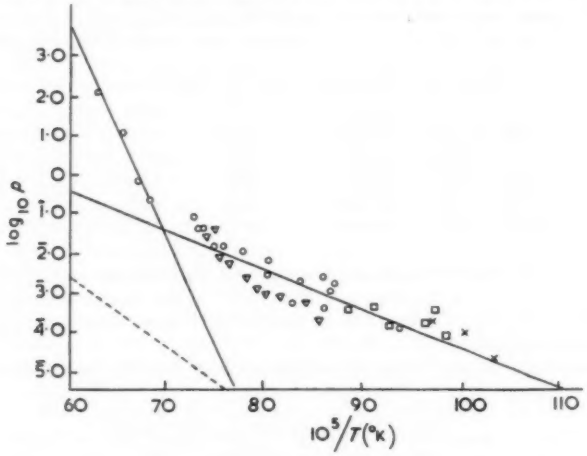
The results set out in Tables 1—5 are shown in Fig. 5. In general, the points are reasonably consistent, particularly when it is remembered that at temperatures below 1000° K, the counts on a target were very low. It is satisfactory that the points from Table 1 agree with those from Tables 2—5 since the results in Table 1 were obtained for an apparatus that differed in many respects.

The values for the four highest temperatures of Table 2 are of particular interest. They appear to indicate that above 1450° K, a more volatile species is present in the vapour. The absolute value of the apparent pressure at these temperatures is uncertain, since the molecular weight of the effusing species enters into the vapour-pressure equation and, in this case, the nature of this species is unknown. Even if the molecular weight were as

high as that of plutonium hexafluoride (353) or as low as the atomic weight of plutonium (239), this would make a maximum difference of $\pm 0{\cdot}4$ log unit to the logarithm of the vapour pressure, and the general shape of the curve would not be greatly affected.

Dawson *et al.*[8] found that when the tetrafluoride was heated on a tantalum filament to an estimated temperature of ~900° C, a residue of trifluoride remained on the filament, and another substance was collected on a cold finger above the filament. On the basis of analyses carried out on milligram quantities of the sublimate, they tentatively suggested that it might be the pentafluoride. On the other hand, Fried and Davidson [9] stated that the trifluoride is produced from the tetrafluoride in a vacuum at ~1000° K, and that it is the trifluoride that is collected by sublimation, but this is not accepted by Brewer *et al.*[10]

FIG. 5. *Vapour pressure* [$\log_{10} p$ (mm. Hg)] *of plutonium tetrafluoride, and* (– – –) *of plutonium.*[11]



From a consideration of the heats of formation and entropies of the compounds involved, Brewer *et al.* deduce that the fluorine pressure over solid tri- and tetra-fluoride at 1000° K should only be about $10^{-8{\cdot}5}$ atmosphere, which would not account for the formation of trifluoride at an appreciable rate in this way; they believe that it is more likely that the formation of the trifluoride in the residue occurs by the reaction $2PuF_4 = PuF_5(g) + PuF_3$.

In the present work, when enough material for analysis remained in the effusion pot at the end of the run, it was found to be plutonium trifluoride. Evaporation of this compound could not account for the high vapour pressures found, as will be seen from the data in Table 6, where the figures for the vapour pressure of trifluoride are those given by Phipps *et al.*[1] and those for the tetrafluoride are interpolated from our work.

TABLE 6. *Vapour pressures* [log *p* (*mm. Hg*)].

Temp. (°K)	1241°	1288°	1347°	1446°	1523°	1577°
V. p. of PuF_4 (this work)	$\bar{3}{\cdot}70$	$\bar{2}{\cdot}00$	$\bar{2}{\cdot}35$	$\bar{2}{\cdot}90$	(9·75)	(1·95)
V. p. of PuF_3 (ref. 1)	$\bar{5}{\cdot}469$	$\bar{4}{\cdot}073$	$\bar{4}{\cdot}810$	$\bar{3}{\cdot}876$	$\bar{2}{\cdot}540$	$\bar{2}{\cdot}991$

It has been suggested that the fluoride might be reduced to plutonium metal by tantalum at this temperature and that the effusing species could be Pu. The vapour

[8] Dawson, Elliott, Hurst, and Truswell, *J.*, 1954, 558.
[9] Fried and Davidson, N.N.E.S., Vol. XIVb, paper 6.11.
[10] Brewer, Bromley, Gilles, and Lofgren, UCRL 633 (1950).

pressure of liquid plutonium has been measured by Phipps *et al.*[11] and a line derived from their data has been added to Fig. 5. This measured vapour pressure of plutonium is too small by a factor of 10^4 to account for our results and the possibility of such a reduction must be rejected.

The vapour pressure of plutonium hexafluoride has also been measured by the present authors with others.[12] The vapour pressure of this compound is 10^2 mm. Hg at 20° C, and is far too high to account for the results under discussion.

It therefore seems most probable that the species effusing above 1450° K is PuF_5, which would be expected to be rather volatile, and may persist as such until it is condensed on the cold target. A further series of experiments was undertaken to isolate this compound on the 10 mg. scale by collecting on a cold finger the vapour from the tetrafluoride heated in a tantalum crucible. These were not successful.

Below 1450° K, the line derived by the method of least squares and plotted in Fig. 5 probably represents the vapour pressure of plutonium tetrafluoride with reasonable accuracy. The only available figures [13] for the vapour pressure of uranium tetrafluoride also lie very close to this line. It is considered that the vapour pressure of plutonium tetrafluoride can be represented by the equation given in the summary of this paper.

Atomic Energy Research Establishment,
Harwell, nr. Didcot, Berks. [*Received, October 28th,* 1960.]

[11] Phipps, Sears, Seifert, and Simpson, Proc. Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955, Vol. VII, p. 382.
[12] Mandleberg, Rae, Hurst, Long, Davies, and Francis, *J., Inorg. Nuclear Chem.*, 1956, **2**, 358.
[13] Mueller, A.E.C.D. 2029 (1948).

---

387. *Transition-metal Complexes of Seven-membered Ring Systems. Part IV.*[1] *Proton Resonance Spectra of Cycloheptatriene Complexes of Group VI Metals.*

By M. A. Bennett, L. Pratt, and G. Wilkinson.

The tricarbonylmolybdenum derivatives of 1,1,4-trimethylcycloheptatriene and 1,1,3,4-tetramethylcycloheptatriene have been prepared. The comparison of high-resolution nuclear magnetic resonance spectra of these compounds and of the unsubstituted compound enables assignments of the spectra to be made.

By using *X*-ray data for the unmethylated complex $C_7H_8Mo(CO)_3$ and a much simplified model, an attempt is made to predict qualitatively the relative line positions for the complex.

The preparation and spectra of Group VI metal complexes of norbornadiene, bicyclo[2,2,2]octa-2,5-diene, and cyclo-octatetraene are given.

In Part I [2] the preparation of tricarbonyl complexes of chromium and molybdenum with cycloheptatriene and some 1-substituted cycloheptatrienes was described. The high-resolution nuclear magnetic resonance spectra of these cycloheptatriene derivatives were very complex and could not be assigned at the time. Subsequent experience with the spectra of some conjugated diene–metal [1,3] and azulene [4] complexes, together with present measurements on molybdenum tricarbonyl derivatives of 1,1,4-trimethyl- and 1,1,3,4-tetramethyl-cycloheptatriene have enabled definite assignments of the spectral lines to be made.

[1] Part III, Burton, Pratt, and Wilkinson, *J.*, 1961, 594.
[2] Abel, Bennett, Burton, and Wilkinson, *J.*, 1958, 4559.
[3] Green, Pratt, and Wilkinson, *J.*, (a) 1959, 3753; (b) 1960, 989.
[4] Burton, Pratt, and Wilkinson, *J.*, 1960, 4290.

XUM

(1) *Nuclear Magnetic Resonance Spectra of Cycloheptatriene Complexes.*—The high-resolution spectra of the parent olefins and of their complexes are given in detail in the Experimental section and are shown, approximately, in the Figure; chemical shifts are given in τ-values.

The spectra of the olefin–metal complexes are quite different from those of the parent hydrocarbons (cf. also refs. 1 and 3). In the parent trienes, there are three types of olefinic proton which give lines occurring at low fields although they are not completely equivalent. The two protons or methyl groups at position 1 are equivalent, probably as a result of a rapid averaging of conformational isomers.

On co-ordination to the metal atom, the changes in the spectra of the three types of olefinic proton present in the hydrocarbons are similar whether the metal atom is chromium, molybdenum, or tungsten. Thus the $\gamma(H_{4,5})$ protons shift upfield slightly (*ca.* 0·2—0·5 p.p.m.) and lie at *ca.* 4·0. The $\beta(H_{3,6})$ protons shift upfield by about 1·5 p.p.m. and lie at *ca.* 5·2, while the $\alpha(H_{2,7})$ protons shift by about 2·5 p.p.m. and lie at *ca.* 6·5. The two methylene protons are also now not equivalent. For the cycloheptatrienechromium complex $C_7H_8Cr(CO)_3$ they differ by *ca.* 1·6 p.p.m.; one is at a higher field than in the cycloheptatriene spectrum and the other, which lies at a lower field than in the cycloheptatriene spectrum, overlaps the lines of the α-protons. For $C_7H_8Mo(CO)_3$, the separation between the methylene group proton lines is smaller (*ca.* 1·0 p.p.m.) than for the chromium compound and both lie at lower fields than for cycloheptatriene. In the $C_7H_8W(CO)_3$ spectrum, both of the methylene proton lines overlap the α-proton lines and the separation between them appears to be small, but the spectrum of this compound was not well resolved, perhaps owing to traces of paramagnetic material produced by decomposition in the solvent used. The same trouble was encountered, though to a smaller extent, with the chromium and molybdenum compounds, whose spectra were slightly broadened. The methyl-substituted cycloheptatrienemolybdenum complexes, which are much more stable than the unsubstituted compound and are less sensitive to air when dissolved, gave sharp spectra. In the methylcycloheptatriene complexes the 1-methyl groups, like the protons of the methylene group in, say, $C_7H_8Cr(CO)_3$, are not equivalent, one methyl line moving upfield and one downfield to give a separation of more than 1 p.p.m. The methyl groups in the 3- and 4-positions move to lower fields in the spectrum of the metal complex, as compared with that of the hydrocarbon.

(2) *Qualitative Estimation of Chemical Shifts.*—It has proved possible to assign in a fairly unequivocal manner the resonance lines in the spectra of various olefin–metal complexes [1,3,4] and we have similarly assigned here the lines for the Group VI metal–cycloheptatriene complexes; also it has been shown that some olefinic protons in a bound conjugated olefin have resonances (due to terminal protons in a conjugated diene system) shifted to higher fields than others. However, it has not been possible, in the absence of accurate *X*-ray crystallographic data, to attempt to correlate the observed chemical shifts with any changes in the bond distances or angles in the hydrocarbon produced by co-ordination to the metal atom. The first *X*-ray crystallographic data on a conjugated olefin–metal complex, $C_7H_8Mo(CO)_3$, are now available, and we have attempted an interpretation of the chemical shifts.

In the structure of cycloheptatrienemolybdenum tricarbonyl [5] the metal atom is on one side of, and almost equidistant (*ca.* 2·35 Å) from, the six olefinic carbon atoms (C_2—C_7) which are virtually planar. The methylene group is bent out of this plane away from the metal atom and the three carbon monoxide groups are approximately diametrically opposite the positions of the double bonds. The C–C distances in the complex are about the same as those found in unco-ordinated conjugated olefins and show alternation corresponding to " double " and " single " bonds; the former are *ca.* 1·36 Å and the latter *ca.* 1·43 Å, while the C–C bonds to the methylene group are *ca.* 1·53 Å.

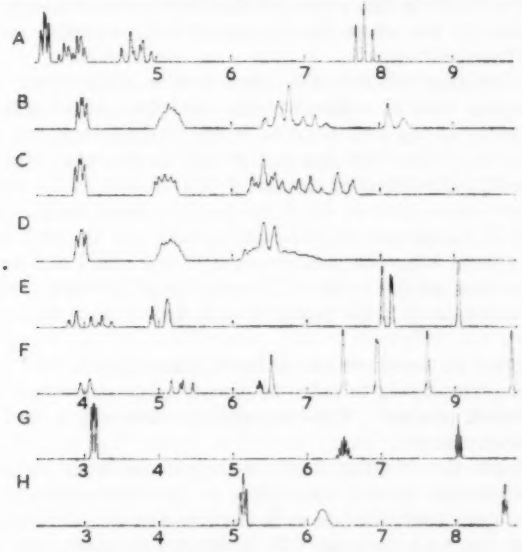
[5] Dunitz and Pauling, *Helv. Chim. Acta*, 1960, **43**, 2188.

XUM

The structure is thus consistent with the presence in the complex of three localised metal–olefin bonds formed by donation of an electron pair from each π-bond in the ring, presumably along the lines suggested for ethylene complexes.[6] There is no indication that σ-bonds are formed between the hydrocarbon and the metal atom, a conclusion in accord with the infrared spectra of the conjugated diene–metal complexes.[1,3,4] The shift of some of the olefinic proton resonances into the high-field region (where aliphatic proton resonances are found) in the conjugated diene– and triene–metal complexes cannot be attributed to the formation of σ-bonds to the metal atom, but can, we believe, now be qualitatively explained, although as yet in a very crude manner (owing to the lack of adequate data and the assumptions necessarily involved) by changes in the " long-range shielding " effects of π-electrons.

The resonance position of a proton in an olefin group depends partly on the diamagnetic shielding by the electrons of the C–H σ-bond. This shielding will alter with changes in the electronegativity of the carbon atom as, for example, when the π-electrons of a double

Proton resonance spectra (56·4 mc./sec.; *scale in τ values*; *magnetic field increases from left to right*).



A, Cycloheptatriene; B, cycloheptatriene-$Cr(CO)_3$; C, cycloheptatriene-$Mo(CO)_3$; D, cycloheptatriene-$W(CO)_3$; E, 1,1,3,4-tetramethylcycloheptatriene; F, 1,1,3,4-tetramethylcycloheptatriene-$Mo(CO)_3$; G, norbornadiene; H, norbornadiene-$Mo(CO)_4$.

bond are utilized in bonding to a transition-metal atom. However, the change should affect all the olefinic protons approximately equally, and it does not seem that this effect would be sufficient to account for the large separations observed in the metal complexes of conjugated olefins.

An important contribution to olefinic proton shifts is the " long-range shielding " effect arising from the electrons in other bonds, notably the π-electrons.[7–10] The magnetic

[6] Dewar, *Bull. Soc. chim. France*, 1951, **79**, 18.
[7] McConnell, *J. Chem. Phys.*, 1957, **27**, 226.
[8] Narashimhan and Rogers, *J. Phys. Chem.*, 1959, **63**, 1388.
[9] Jackman and Wiley, *J.*, 1960, 2881.
[10] Jackman, " Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," Pergamon Press, London, 1959.

XUM

moment induced in the π-electrons by the applied magnetic field produces small additional magnetic fields at the protons, thereby altering their resonance positions. These small magnetic fields do not average to zero over all orientations because the diamagnetic susceptibility of π-electrons is anisotropic. The correct expression [8] for the shielding field is complicated and requires a knowledge of the three principal components of the susceptibility of the π-electrons, but a qualitative explanation of the long-range shielding effects in unco-ordinated olefins is obtained if the olefin group is represented by a point magnetic dipole. This dipole is placed at the electrical centre of the bond, *i.e.*, at the centre of the C–C σ-bond axis, and points in the direction of maximum magnetic susceptibility, *i.e.*, perpendicular to the plane of the C–H and C–C σ-bonds. The shielding field decreases with the inverse cube of the distance, away from the bond centre, and also varies with direction. The field is positive in regions above and below the plane of the olefin group inside solid cones extending from the point dipole symmetrically about its axis (for a diagram see ref. 10). Protons in these regions will experience an increased shielding producing a shift to higher fields. The field is negative in the region outside the cones and for a given distance is greater in the plane perpendicular to the dipole. The protons in a normal olefin lie in this plane and should experience a large negative shielding and this is believed to be the reason for the appearance of olefinic proton resonances in low-field regions of the spectrum.

The long-range shielding will certainly alter when π-electrons are involved in metal bonding. It is obvious that in a metal–olefin bond the electrical centre of this bond cannot be at the centre of the C=C bond as in the hydrocarbon but must be displaced towards the metal atom. Also, the direction of the maximum susceptibility of the bond depends on the directional relation of the metal to C=C axis; such changes would affect both the distance and orientation of the point dipole relative to the olefin protons. We can note here that in complexes of cyclic polyolefins and of such chelating dienes as norbornadiene, butadiene, etc., the conformation of the olefin will not allow the metal atom to occupy a position normal to the C=C bond axis as in ethylene complexes. In fact the line joining the metal atom to the centre of each double bond may not even be the line of maximum density.

We have attempted to represent the induced magnetic moment of the metal–olefin bond by a point magnetic dipole in order to calculate the long-range shielding effect on the co-ordinated olefinic protons. This procedure is obviously a vast oversimplification in view of the unknown factors.

In order to calculate the shielding effect on the protons in the complex it is necessary first to estimate where the proton resonances in the unco-ordinated cycloheptatriene skeleton fixed in the same configuration as in the complex would lie in the absence of any long-range shielding due to π-electrons. It is difficult to make this estimate, but it is clear that they would move upfield from the olefinic region and would probably lie close together. While the corrected position of the methylene protons would be *ca.* τ 8—8·5, the other protons could be grouped in the region 5·5—8. The shielding due to the π-contribution in the metal–olefin bonds is then superimposed. The π-contribution in the complex we take as being that due to three identical magnetic point dipoles located along the metal-to-double-bond axis. Each proton in the co-ordinated olefin experiences a contribution from each of the three dipoles, and in theory the algebraic sum of these contributions for each proton can be calculated with the dipoles in different orientations, the aim being to reproduce the observed resonance pattern. In the absence of a reliable estimate of the " skeletal " resonance positions, a variety of arrangements of the magnetic dipole of the metal–olefin bond are possible. However, the observed spectra of the complex being considered it seems likely that the algebraic sums of the three dipole contributions should give a net negative value for the γ-protons, a slight negative value for the β-protons, and a small negative or positive value for the α-protons. The methylene-protons should be different and have a negative contribution.

XUM

We have tried several arrangements and the type that best seems to reproduce the relative shifts is one where the magnetic point dipole points along the metal to C=C axis and is located at about one-third to one-quarter of the distance towards the metal atom. In this orientation, each olefin proton receives a small negative contribution from the dipole of its own metal–olefin bond but the contributions from the other two dipoles differ for the α-, β-, and γ-protons. The α-, β-, and γ-protons receive negative contributions from other two dipoles but their magnitudes decrease in the order $\alpha > \beta > \gamma$. Also, the two methylene-protons receive different negative contributions, the outer proton receiving the more negative. The magnitude of these field contributions depends on the magnetic moment of the point dipoles and we can use the observed separation between the two methylene-protons (*ca.* 1 p.p.m.) to convert the contributions to p.p.m. The addition of these contributions as p.p.m. to the above skeletal positions then reproduces fairly well the main features of the observed spectrum.

The relative shifts of the methyl groups in methyl-substituted cycloheptatriene complexes also seem to agree with this model; the estimated shifts are averaged over all orientations to allow for free rotation of the methyl groups.

The chromium and tungsten complexes have infrared and nuclear resonance spectra very similar to those of the molybdenum compound, and their structures are presumably similar. The nuclear magnetic resonance spectra differ mainly in the position for the methylene-protons. This is not unexpected, since small changes in the bond angles and distances in the metal–olefin group can produce larger changes in the orientation of the methylene group, thereby changing the field contribution at the two protons. The close similarity of the three groups of olefinic resonances in the chromium, molybdenum, and tungsten compounds suggests that the resonance positions are little dependent on the nature of the metal carbonyl part of the molecules.

(3) *Norbornadiene and Other Olefin–Metal Complexes.*—The proton resonance spectra of the norbornadiene complexes of molybdenum and chromium show three groups of lines similar to those from norbornadiene itself, indicating that the olefin has not isomerised in the complexes. Relative to their positions in spectra of the parent olefin, the methylene-protons occur at higher fields and the tertiary protons at slightly lower fields. The olefin–protons show larger shifts to higher fields although they are not so large as the shift found for the norbornadieneiron tricarbonyl complex.[3b] Although norbornadiene is unconjugated, it has a rigid structure which probably does not allow the olefin–metal axis to be perpendicular to the olefin groups, a situation similar to that of the cyclic olefin complexes. The observed shifts are compatible with a model involving two metal–olefin dipoles in orientations similar to those assumed for the cycloheptatriene complex.

The shifts in metal complexes of conjugated dienes [1,3] can also be explained qualitatively by similar models with two point dipoles. The type of structure usually accepted for these compounds is similar to that of the cycloheptatriene complex with the metal atom on one side of a planar olefin group. Again in this type of structure the metal–olefin axis is not perpendicular to the plane of the olefin group; rough calculations, with the dipole assumed along the metal to C=C bond about one-third towards the metal atom, predict a large separation between the central and the terminal protons of the diene system, as we have observed.

In the ethyleneplatinum compounds, on the other hand, the metal–olefin axis is perpendicular to the plane of the ethylene molecule. On our present model, the point dipole would point along this direction, as in ethylene itself. The four protons would experience the same shielding field and, if the electrical centre of the bond is not displaced too far towards the metal atom, the shielding field would still be negative and could be almost as great as in ethylene itself. It has been found that the proton resonance in ethyleneplatinum complexes is little shifted from ethylene itself.[11]

[11] Powell and Sheppard, *J.*, 1960, 2519.

XUM

We have also considered other models in which the dipole is oriented either perpendicular to the metal to C=C plane or parallel to the C=C axis. These orientations do not produce chemical shifts in the right directions, especially for methylene-protons in the cycloheptatriene complexes. The parallel, or at least some angular, orientation might be the most satisfactory if it is accepted, as has often been discussed that there is an appreciable amount of π-bonding between the metal atom and the olefin group owing to back-donation from the metal atom into anti-bonding π-orbitals on the carbon atoms. Whilst we have found that the orientation of the dipole along the metal to C=C axis is more satisfactory, this really gives no indication of the actual electron-density distribution in the metal–olefin bond.

We have not considered the contributions from other groups present in the molecules, such as the carbonyl groups, but these alone do not appear to produce sufficiently large effects to account for the olefinic shifts—for example, the olefinic resonances in the cyclopentadieneiron compounds are the same when the other groups present are so different as benzene,[3b] three carbonyls, or one triphenylphosphine and two carbonyl groups.[12]

Experimental

Microanalyses and molecular-weight determinations (ebullioscopic in benzene) were done by the Microanalytical Laboratory of this College.

Starting Materials.—1,1,3,4-Tetramethylcycloheptatriene was prepared by treating eucarvone [from (+)-carvone [13]] with methyl-lithium and dehydrating the resulting alcohol.[14] 1,1,4-Trimethylcycloheptatriene was obtained from Professor Alder's laboratory, Cologne. Cycloheptatriene and norbornadiene were generously presented by Shell Chemical Co., cyclooctatetraene by the British Oxygen Co., the bicyclo-octadiene by Professor Grob, Basle, and metal carbonyls by the Climax Molybdenum Co.

1,1,4,-*Trimethylcycloheptatrienemolybdenum Tricarbonyl.*—The olefin (2 g.) and excess of molybdenum carbonyl (5 g.) were heated in aromatic-free light petroleum (b. p. 100—120°) (40 ml.) under nitrogen for 7 hr. Removal of solvent and excess of carbonyl at 40°/1 mm. left red crystals (3·8 g.) which on sublimation at 90—100°/10^{-4} mm. gave the orange-red *complex*, m. p. 86—87° (80—90% yield) (Found: C, 49·8; H, 4·8; O, 15·5; Mo, 30·6%; *M*, 312. $C_{13}H_{14}MoO_3$ requires C, 49·7; H, 4·8; O, 15·3; Mo, 30·5%; *M*, 314).

1,1,3,4-*Tetramethylcycloheptatrienemolybdenum Tricarbonyl.*—This *complex* was prepared in a similar manner and sublimed at 120—130°/10^{-4} mm. as red crystals, m. p. 119—120° (yield 80—90%) (Found: C, 51·3; H, 5·0; O, 14·8; Mo, 29·4%; *M*, 324. $C_{14}H_{16}MoO_3$ requires C, 51·2; H, 4·9; O, 14·6; Mo, 29·2%; *M*, 328).

The two preceding compounds can also be purified by crystallisation from light petroleum (b. p. 30—40°) at −78°. These methyl-substituted compounds are more soluble in organic solvents and are both thermally, and, in polar solvents, oxidatively, more stable than the corresponding cycloheptatriene compound. Thus acetone solutions of the latter are decomposed by air within a few minutes, whereas the methyl-substituted compounds can be held in solution for several hours. This enhanced stability can be attributed to the electron-donor effect of the methyl groups which eases transfer of electron density from the olefin to the metal atom, and hence the bond strength.

Cycloheptatrienetungsten Tricarbonyl.—The hexacarbonyl (3 g.) and olefin (10 ml.) in 2,2′-dimethoxydiethyl ether (40 ml.) were heated at 190° in nitrogen for 6 hr. After evaporation at 80°/0·5 mm. the dark red oily residue was extracted with hot light petroleum (b. p. 60—80°; 3 × 15 ml.) and, after reduction to *ca.* 30 ml., the extract was cooled to −78°. The red crystals sublimed at 80—90°/10^{-4} mm. as needles, m. p. 117—118° (yield, 0·3 g.) (Found: C, 33·3; H, 2·3; O, 13·1%; *M*, 355. $C_{10}H_8O_3W$ requires C, 33·4; H, 2·2; O, 13·3%; *M*, 360). The tungsten *compound* is similar to the chromium and the molybdenum analogue [3] and appears to be intermediate between them in stability to air-, both in solution and in the solid state; the

[12] Davison, Pratt, and Wilkinson, unpublished results.
[13] Corey and Burke, *J. Amer. Chem. Soc.*, 1956, **78**, 174.
[14] Corey, Burke, and Remers, *J. Amer. Chem. Soc.*, 1956, **78**, 180; Alder, Kaiser, and Schumacher, *Annalen*, 1957, **602**, 80.

XUM

compound has also recently been obtained by the reaction of cycloheptatriene with cyclo-octa-1,5-dienetungsten tetracarbonyl.[15]

Norbornadienechromium Tetracarbonyl.—The hexacarbonyl (5 g.) and olefin (8 ml.) were refluxed in aromatic-free light petroleum (b. p. 100—120°; 40 ml.) under nitrogen for 2 days. After evaporation at 50°/10^{-2} mm. sublimation gave the orange-yellow *tetracarbonyl*, m. p. 92—93° (yield, 1·7 g.) (Found: C, 51·8; H, 3·3; O, 24·7%; *M*, 251. $C_{11}H_8CrO_4$ requires C, 51·6; H, 3·1; O, 25·0%; *M*, 256).

Norbornadienemolybdenum Tetracarbonyl.—This was prepared as in the preceding case, except that the mixture was refluxed for only 20 hr. Removal of volatile material left a leathery polymer mixed with crystals; the latter were extracted with boiling light petroleum (b. p. 40—60°; 3 × 15 ml.), and the filtered extract was cooled to −78° to give pale yellow plates, m. p. 77—78° (yield, 60—70%) (Found: C, 44·0; H, 2·9; O, 21·3; Mo, 32·0%; *M*, 304. Calc. for $C_{11}H_8MoO_4$: C, 44·0; H, 2·7; O, 21·3; Mo, 32·0%; *M*, 300). This compound, which has previously been noted briefly,[16] sublimes in a vacuum below 80° but at higher temperature decomposes extensively.

The corresponding tungsten compound can be obtained in very low yield when the reagents are refluxed in 2,2′-dimethoxydiethyl ether; it was identified only by its infrared spectrum.

As in the cycloheptatriene series, the norbornadienechromium complex is more stable to air and more deeply coloured than the molybdenum complex. However, the latter is considerably more stable to air than cyclo-octa-1,5-dienemolybdenum tetracarbonyl, which confirms other evidence that norbornadiene is the most effective chelating diolefin so far investigated.

Bicyclo[2,2,3]*octa-2,5-diene-* (A) *and cyclo-octa-1,5-diene-molybdenum Tetracarbonyls* (B).[17]—These *compounds* were obtained by heating the hexacarbonyl (1 g.) and olefin (0·5 g.) in light petroleum (b. p. 100—120°; 30 ml.) under nitrogen for 20 hr. After removal of volatile matter the complexes crystallised from light petroleum (b. p. 40—60°) at −78° as yellow plates (A), m. p. 80° (decomp.) (Found: C, 45·6; H, 3·5; O, 20·6; Mo, 30·1%; *M*, 312. $C_{12}H_{10}MoO_4$ requires C, 45·8; H, 3·2; O, 20·4; Mo, 30·6%; *M*, 314), or cream needles (B), m. p. 119—120° (decomp.) (yield 40%) (Found: C, 45·3; H, 4·0; O, 20·4; Mo, 30·6%; *M*, 311. $C_{12}H_{12}MoO_4$ requires C, 45·6; H, 3·8; O, 20·2; Mo, 30·6%; *M*, 316).

Dicyclo-octatetraenemolybdenum Tetracarbonyl.—The hexacarbonyl (10 g.) and cyclo-octatetraene (5 ml.) were refluxed in light petroleum (b. p. 100—120°) for 20 hr. After evaporation of the red-brown solution at 50°/10^{-2} mm., the residue was extracted with hot benzene (3 × 20 ml.). After reduction to 15 ml., the extract was chromatographed on alumina with benzene as eluant. Two bands were obtained, the first of which gave pale yellow crystals (0·5 g.), from 1 : 1 benzene–light petroleum (b. p. 60—80°), of *dicyclo-octatetraenemolybdenum tetracarbonyl*, m. p. 190—192° (decomp.) (Found: C, 57·8; H, 4·3; O, 15·3; Mo, 23·3%; *M*, 419. $C_{20}H_{16}MoO_4$ requires C, 57·7; H, 3·9; O, 15·4; Mo, 23·0%; *M*, 416). The second band contained a rather air-sensitive substance, in low yield; this was not characterised. The first compound is insoluble in light petroleum but sublimed at *ca.* 180° in a vacuum. On catalytic hydrogenation of the complex (9·319 mg.) in ethyl acetate over Adams catalyst, 0·496 ml. (S.T.P.) of hydrogen was absorbed, corresponding to 1 mol. of hydrogen and indicating the presence of a double bond. It seems reasonable to conclude that this molybdenum tetracarbonyl complex has bound to it a cyclo-octatetraene dimer with three double bonds, only the two conjugated double bonds being utilized in bonding to the metal atom. However, since the dimer with three double bonds [18] does not appear to react with molybdenum carbonyl the co-ordinated olefin may have a different configuration; the nuclear magnetic resonance spectrum of the compound is very complicated and we have not as yet been able to interpret it.

Infrared Spectra.—Spectra were recorded on a Perkin–Elmer Model 21 instrument with sodium chloride and calcium fluoride optics and carbon disulphide, chloroform, and carbon tetrachloride in the appropriate regions. The spectra of the cycloheptatriene complexes are similar to that for $C_7H_8Mo(CO)_3$ [3] except for additional bands for the methyl-substituted complexes; the norbornadiene complexes have spectra similar to those of other norbornadiene

[15] Manuel and Stone, *Chem. and Ind.*, 1960, 231.
[16] Pettit, *J. Amer. Chem. Soc.*, 1959, **81**, 1266.
[17] Manuel and Stone, *Chem. and Ind.*, 1959, 1349; Bennett and Wilkinson, *ibid.*, 1959, 1516; Fischer and Frohlich, *Chem. Ber.*, 1959, **92**, 2995.
[18] Jones, *J.*, 1953, 2036.

XUM

complexes.[19] Norbornadienechromium tetracarbonyl shows four carbonyl bands, at 2033vs, 1959ms, 1944vs, and 1913vs cm.$^{-1}$, but for the molybdenum and tungsten compounds only three bands could be resolved.

Nuclear Magnetic Resonance Spectra and Assignments.—Proton resonance spectra were recorded at 56·4 Mc./sec. and 22° ± 1° on a Varian instrument. Carbon tetrachloride solutions were used and line positions are given in τ values (10·00 minus the position in p.p.m. on low-field side of tetramethylsilane as internal reference). Cycloheptatriene has been measured previously.[1]

1,1,4-*Trimethylcycloheptatriene.* 3·81, unsymmetrical doublet (6·2 c./sec.), H_5 split by H_6 (AB pair); 4·12, double doublet, H_6 split by H_5 (6·2 c./sec.) and H_7 (~9·0 c./sec.); 4·17, unsymmetrical doublet (~9·0 c./sec.), H_3 split by H_2 (AB pair); 5·07 and 5·04, H_2 and H_7 each split into an unsymmetrical doublet (AB pair) by H_2 and H_6 respectively; 8·01, single (width 3 c./sec.), 4-methyl group; 9·03, single (width 1 c./sec.), 1-methyl groups.

1,1,3,4-*Tetramethylcycloheptatriene.* 3·84, unsymmetrical doublet (6·2 c./sec.), H_5 split by H_6 (AB pair); 4·22, double doublet, H_6 split by H_5 (6·2 c./sec.) and by H_7 (9·6 c./sec.); 5·03, doublet (9·6 c./sec.), H_7 split by H_6; 5·16, *ca.* single, H_2 (overlaps one component of H_7); 8·03, singlet, 4-methyl group; 8·15, doublet (1·2 c./sec.), 3-methyl group split by H_2; 9·06, singlet, two 1-methyl groups.

Cycloheptatrienemolybdenum tricarbonyl. 3·95, double doublet (outer separation 7·6 c./sec., inner, ~2 c./sec.), $H_4 + H_5$ split by each other and by H_3 and H_6; 5·11, ⩾ five components, *ca.* 4 c./sec. separation, H_3 and H_6 split by H_2 and H_4 and by H_5 and H_7, respectively; *ca.* 6·5, double triplet (?), H_2 and H_7 split by H_3 and H_6, respectively, and by $>CH_2$ protons; *ca.* 6·9, complex, one $>CH_2$ proton; *ca.* 7·55, doublet (AB pair, 12 c./sec.), one proton of $>CH_2$ split by the other.

1,1,4-*Trimethylcycloheptatrienemolybdenum tricarbonyl.* 4·12, doublet (AB pair, 7·2 c./sec.), H_5 split by H_6; *ca.* complex, $H_6 + H_3$; 6·52, doublet (*ca.* 9·5 c./sec.), H_2 and H_7 split by H_3 and H_7, respectively; 7·48, single, 4-methyl group; 8·60, single, and 9·70, single, the 1-methyl groups.

1,1,3,4-*Tetramethylcycloheptatrienemolybdenum tricarbonyl.* 4·02, doublet (AB pair, 7·1 c./sec.), H_5 split by H_6; 5·31, double doublet, H_6 split by H_5 (7·1 c./sec.) and H_7 (*ca.* 9·0 c./sec.); 6·28, doublet and triplet (?), H_7 split by H_6 (8·6 c./sec.) and H_5; 6·44, single (width 2·3 c./sec.), H_2; 7·49, single, 4-methyl group; 7·94, doublet (splitting *ca.* 1·5 c./sec.), 3-methyl group; 8·63 and 9·77, both single, two 1-methyl groups.

Cycloheptatrienechromium tricarbonyl. 3·99, double doublet (7·6 c./sec. overall, 2 c./sec. inner separation), $H_4 + H_5$ split by each other and by H_3 and H_6; 5·17, complex, unresolved, H_3 plus H_6; *ca.* 6·6, H_3 and H_7, *ca.* 7·1, one of $>CH_2$ protons; 8·23, unsymmetrical doublet (*ca.* 12·6 c./sec.), one $>CH_2$ proton split by the other (AB pair).

Cycloheptatrienetungsten tricarbonyl. 3·96, double doublet (7·2 c./sec. overall, inner pair unresolved), H_4 and H_5; 5·18, complex but unresolved, H_3 and H_6; 6·1—7·2, overlapping bands of H_3, H_7 and both $>CH_2$ protons.

Norbornadiene. The spectrum has been given previously [3b] and a complete analysis of the spin-coupling interactions has also been given.[20]

Norbornadienechromium tetracarbonyl. 5·58, " triplet " (4·8 c./sec. overall) olefinic protons; 6·27, complex, unresolved, tertiary protons; 8·70, triplet (1·4 c./sec.), $>CH_2$ protons split by tertiary protons.

Norbornadienemolybdenum tetracarbonyl. 5·15, " triplet " (4·4 c./sec. overall), olefinic protons; 6·22 (no structure resolved; width *ca.* 8 c./sec.), tertiary protons; 8·67, triplet (1·3 c./sec.), $>CH_2$ protons split by tertiary protons.

We thank the Department of Scientific and Industrial Research for a studentship (to M. A. B.), and the Hercules Powder Co. for research expenses.

Inorganic Chemistry Research Laboratories,
Imperial College of Science and Technology,
S. Kensington, London, S.W.7.

[*Received, November 2nd,* 1960.]

[19] Abel, Bennett, and Wilkinson, *J.*, 1959, 3178.
[20] Mortimer, *J. Mol. Spectroscopy*, 1959, **3**, 528.

XUM

388. *Activation Parameters for S_N1 Solvolysis in 50% Aqueous Acetone.*

By E. F. Brittain, G. Kohnstam, A. Queen, and B. Shillaker.

The rates of hydrolysis of t-butyl chloride, *p*-nitrodiphenylmethyl chloride and *p*-methylbenzylidene chloride have been examined in 50% aqueous acetone. Comparison with earlier results for benzylidene chloride and benzotrichloride in the same solvent shows that, within the limits of experimental error, the ratio of the heat capacity of activation to the entropy of activation is independent of the nature of the substrate for S_N1 reactions.

Evidence has been accumulating showing that the solvolysis of organic halides and sulphonates is associated with a negative temperature coefficient for the activation energy,[1-4] and hence with a negative heat capacity of activation, $\Delta C^{\ddagger} = (dE/dT) - \boldsymbol{R}$. It has been suggested that the decrease in heat capacity on passing into the activated complex arises mainly, if not entirely, from the increase in solvation associated with the development of electric charges,[2,3a] and that this factor is also almost entirely responsible for the entropy of activation, $\Delta S^{\ddagger}$, in S_N1 reactions.[3b,5] On this view, the ratio $\Delta C^{\ddagger}/\Delta S^{\ddagger}$ should be independent of the nature of the substrate in reaction by mechanism S_N1.[3b] This hypothesis is supported by the results for the solvolysis of benzylidene chloride and benzotrichloride in 50% aqueous acetone and 50% aqueous ethanol,[3b] and by results for the reactions of substituted diphenylmethyl chlorides with 70% aqueous acetone.[3c] The reactions of t-butyl chloride, *p*-nitrodiphenylmethyl chloride, and *p*-methylbenzylidene chloride with 50% aqueous acetone have now been studied in order to obtain further information about the effect of substrate-structure on the value of $\Delta C^{\ddagger}/\Delta S^{\ddagger}$ in S_N1 reactions.

Some comment on the reaction mechanism is necessary before discussing the present results since the assignment of mechanism S_N1 to the reaction between aqueous solvents and benzylidene chloride and benzotrichloride has been queried as a result of solvolytic studies in water and deuterium oxide.[6] Much of the evidence that the rate-determining step in the solvolysis of these compounds (and, by analogy, in the solvolysis of *p*-methylbenzylidene chloride) is the ionisation of one of the C–Cl linkages has already been discussed.[3a] Abstraction of an α-hydrogen atom, as in the hydrolysis of chloroform,[7] might be considered as rate-determining in the hydrolysis of benzylidene chloride but the absence of any accelerating effect by added hydroxide ions [8] argues strongly against this mechanism which could also not operate in the solvolysis of benzotrichloride, a compound without α-hydrogen atoms. Complete hydrolysis of both compounds yields the amount of hydrochloric acid to be expected on the assumption of nucleophilic substitution, the effect of α-chlorination on the rate of hydrolysis of benzylidene chloride is similar to that in other compounds known to react by mechanism S_N1, and it will be shown later in this paper that the introduction of a *p*-methyl group alters the rate of hydrolysis in a manner entirely consistent with the assumption of S_N1 hydrolysis for the parent compound and

[1] Robertson, *Proc. Roy. Soc.*, 1959, *A*, **252**, 273; Hamilton and Robertson, *Canad. J. Chem.*, 1959, **37**, 966, and earlier papers.
[2] (*a*) Tommila, Tilikainen, and Voipio, *Ann. Acad. Sci. Fennicae*, 1955, *A*, II, No. 65; (*b*) Tommila, Paakkala, Virtanen, Erva, and Varila, *ibid.*, 1959, *A*, II, No. 91.
[3] (*a*) Bensley and Kohnstam, *J.*, 1956, 287; (*b*) *J.*, 1957, 4747; (*c*) Kohnstam, *J.*, 1960, 2066.
[4] McKinley-McKee and Moelwyn-Hughes, *Trans. Faraday Soc.*, 1952, **48**, 247; Glew and Moelwyn-Hughes, *Proc. Roy. Soc.*, 1952, *A*, **211**, 254; Moelwyn-Hughes, *ibid.*, 1953, *A*, **220**, 386.
[5] Evans and Hamann, *Trans. Faraday Soc.*, 1951, **47**, 25; Buchanan and Hamann, *ibid.*, 1953, **49**, 1425; Burris and Laidler, *ibid.*, 1955, **51**, 1497.
[6] Laughton and Robertson, *Canad. J. Chem.*, 1959, **37**, 1491.
[7] Hine, *J. Amer. Chem. Soc.*, 1950, **72**, 2438.
[8] Olivier and Weber, *Rec. Trav. Chim.*, 1934, **53**, 869.

XUM

its substituted derivative. It therefore seems likely that factors, which have yet to be explained, complicate mechanistic interpretations based on the results of isotopic changes in the solvent. t-Butyl chloride and diphenylmethyl chloride have long been assumed to undergo S_N1 solvolysis, both compounds show considerable steric hindrance with respect to bimolecular (S_N2) reaction,[9] and it has recently been shown that not more than a small fraction of the racemisation of *p*-chlorodiphenylmethyl chloride in acetone, a poor ionising solvent, could occur bimolecularly.[10] It seems reasonable to assume that analogous considerations apply to *p*-nitrodiphenylmethyl chloride. Evidence has recently been presented to show that the reaction of diphenylmethyl bromide with nucleophilic reagents in nitromethane involves both first- and second-order components, the latter being interpreted as arising from bimolecular attack on the partially heterolysed substrate.[11] The very rapid bimolecular attack by azide ions in nitromethane is, however, not observed with diphenylmethyl chloride in aqueous acetone where, within the limits of experimental error, all the azide intervention occurs by the unimolecular mechanism.[12] Water, a much less powerful nucleophilic agent than azide ions, is even less likely to show bimolecular attack. It is therefore considered that the reaction between 50% aqueous acetone and

TABLE 1. *Kinetic data for solvolysis in 50% aqueous acetone.*

(k in sec.$^{-1}$, E in kcal., dE/dT in cal. °K^{-1}.)

(i) *p*-Nitrodiphenylmethyl chloride.

Temp.	10^6k	Temp.	$E_{obs.}$	$E_{calc.}$
20·60°	5·318 ± 0·012$_3$	25·12°	22·48$_5$ ± 0·060	22·48$_6$
29·65	16·81 ± 0·034$_5$	34·48	22·18$_7$ ± 0·056	22·19$_1$
39·31	52·55 ± 0·10$_6$	44·35	21·88$_9$ ± 0·049	21·88$_0$
49·39	158·1 ± 0·22$_8$	54·90	21·54$_3$ ± 0·052	21·54$_3$
60·41	480·0 ± 0·85$_9$			

$dE/dT = -31·5 \pm 2·4$

(ii) t-Butyl chloride.

Temp.	10^6k	Temp.	$E_{obs.}$	$E_{calc.}$
0·00°	9·120 ± 0·021$_4$	5·00°	21·08$_5$ ± 0·041	21·09$_7$
10·00	35·95 ± 0·046$_4$	14·90	20·84$_2$ ± 0·048	20·84$_3$
19·81	124·2$_5$ ± 0·31$_6$	24·68	20·65$_9$ ± 0·061	20·60$_4$
29·55	389·0 ± 0·85$_6$	34·70	20·32$_6$ ± 0·051	20·35$_4$
39·86	1183·$_7$ ± 2·0$_6$			

$dE/dT = -25·0 \pm 2·1$

(iii) *p*-Methylbenzylidene chloride.

Temp.	10^6k *	Temp.	$E_{obs.}$	$E_{calc.}$
0·00°	2·682 ± 0·0060$_9$	5·02°	21·82$_8$ ± 0·051	21·80$_7$
10·05	11·17 ± 0·026$_9$	14·75	21·46$_9$ ± 0·057	21·44$_6$
19·46	38·08 ± 0·081$_9$	24·68	20·98$_6$ ± 0·043	21·07$_8$
29·90	132·0 ± 0·17$_4$	34·84	20·75$_4$ ± 0·053	20·70$_1$
39·77	391·4 ± 0·95$_1$			

$dE/dT = -37·1 \pm 3·5$

* Per replaceable chlorine atom.

the present compounds (as well as the two compounds previously studied in this solvent [3a]) occurs entirely by mechanism S_N1.

The kinetic results now obtained are summarised in Table 1; all the errors quoted are standard errors. Energies of activation, $E_{obs.}$, were obtained from rates at adjacent temperatures by use of the Arrhenius equation and refer to the mean temperature of the interval,[3a] the temperature coefficient of the activation energy, dE/dT, was obtained from the slope of the " best " straight plot of E against T, and $E_{calc.}$ refers to the activation

[9] de la Mare, Fowden, Hughes, Ingold, and Mackie, *J.*, 1955, 3200; Hughes and de la Mare, *J.*, 1956, 845.

[10] Gall and Winstein, *Tetrahedron Letters*, 1960, No. 2, 31.

[11] Pocker, *J.*, 1959, 3939, 3943.

[12] Bateman, Church, Hughes, Ingold, and Taher, *J.*, 1940, 979.

energies required by this line. This method of calculation assumed that dE/dT is constant over the temperature range investigated, and it can be seen that the observed and calculated activation energies agree within the limits of experimental error. The temperature dependence of dE/dT is therefore small and the present results are not sufficiently accurate to allow its recognition.

The reaction of t-butyl chloride with a number of acetone–water mixtures has already been studied by Tommila and his co-workers.[2a] Their values for the energy and entropy of activation in 46% (w/w) acetone agree fairly well with those calculated from the present results in our solvent [which corresponds to 44·2% (w/w) acetone] at 32·5°, the mean temperature of the previous work; unfortunately, the results in 46% (w/w) acetone are not sufficiently accurate to yield a value for the temperature coefficient of the activation energy. In the present solvent, this coefficient is about one-half the mean value previously reported for a number of highly aqueous acetone–water mixtures,[2a] and is also less than the value already estimated for reaction with pure water.[13] There is however no reason why this coefficient should be independent of the solvent composition.

Discussion

p-Methylation in Benzylidene Chloride.—The effect of a *p*-methyl substituent on the rate of hydrolysis of benzylidene chloride can be found by combining the present results with those obtained earlier for the parent compound.[3a] The changes in the rate of solvolysis resulting from this substitution are given in Table 2 for a number of compounds known to react by mechanism S_N1. It can be seen that the relative rates (k_{Me}/k_H) decrease with increasing facility for electron donation to the reaction centre by the groups, other than the phenyl group to be substituted, which are directly attached to the central carbon atom, probably because of the resulting reduction in the demand for electrons at the site of substitution (cf. ref. 3*c*). Admittedly, the largest value of k_{Me}/k_H also corresponds to the best ionising solvent in this series but the effect of *para*-substituents on the rates of S_N1 reactions is usually fairly insensitive to changes in solvent.[3c,14] It is also noteworthy that the acceleration caused by *p*-methylation in benzylidene chloride almost entirely

Table 2. *The effect of* p-*methyl substituents on the rates of* S_N1 *reactions at* 25°

Compound	$Ph{\cdot}CHCl_2$	$Ph{\cdot}CHMe{\cdot}Cl$ [a]	$Ph{\cdot}CHPh{\cdot}Cl$ [b]	$Ph{\cdot}CMe_2{\cdot}Cl$ [c]	$Ph{\cdot}CPh_2{\cdot}Cl$ [d]
Solvent	50% acetone *	79·5% dioxan *	80% acetone *	90% acetone *	60% ether †
k_{Me}/k_H	79·2	56·2	21·4	26·0	4·1

* Water as second component. † Ethanol as second component.
[a] Mechelynk-David and Fierens, *Tetrahedron*, 1959, **6**, 232. [b] Hughes, Ingold, and Taher, *J.*, 1940, 949. [c] Brown, Brady, Grady, and Bonner, *J. Amer. Chem. Soc.*, 1957, **79**, 1897. [d] Branch and Nixon, *ibid.*, 1936, **58**, 492.

Table 3. *Activation parameters for* S_N1 *solvolysis in* 50% *aqueous acetone at* 50°.

E and $\Delta S^\ddagger$ from the " best " straight plots of $E_{obs.}$ against T and $\Delta S^\ddagger_{obs.}$ against log T, respectively. The standard errors which are quoted for E and $\Delta S^\ddagger$ arise from the standard error in dE/dT. E is in kcal., $\Delta S^\ddagger$ in cal. °K^{-1}.

Compound	E	$-\Delta S^\ddagger$	$-\Delta C^\ddagger$	$\Delta C^\ddagger/\Delta S^\ddagger$
$PhCCl_3$ *†	19·315 ± 0·129	16·17 ± 0·42	45·8 ± 4·3	2·83 ± 0·28
$PhCHCl_2$ *†	22·917 ± 0·018	11·33 ± 0·05	29·7 ± 3·6	2·62 ± 0·32
$p\text{-}MeC_6H_4{\cdot}CHCl_2$ *	20·140 ± 0·105	11·97 ± 0·35	39·1 ± 3·5	3·27 ± 0·31
$p\text{-}NO_2{\cdot}C_6H_4{\cdot}CHPhCl$	21·702 ± 0·032	10·81 ± 0·21	33·5 ± 2·4	3·10 ± 0·22
Bu^tCl	19·971 ± 0·063	10·28 ± 0·09	27·0 ± 2·1	2·63 ± 0·21

* $\Delta S^\ddagger$ and $\Delta C^\ddagger/\Delta S^\ddagger$ per replaceable chlorine atom. † Calculated from Bensley and Kohnstam's data.[2a]

results from a reduction in the activation energy, the entropy of activation being virtually unchanged (see Table 3). This type of behaviour is to be expected in S_N1 reactions—and

[13] Robertson, Heppolette, and Scott, *Canad. J. Chem.*, 1959, **37**, 803.
[14] Brown and Okamoto, *J. Amer. Chem. Soc.*, 1957, **79**, 1909.

XUM

is also observed with the other compounds listed in Table 2—and therefore supports the assignment of mechanism S_N1 to the hydrolysis of benzylidene chloride.

$\Delta C^{\ddagger}/\Delta S^{\ddagger}$.—Activation parameters for S_N1 solvolysis in 50% aqueous acetone are given in Table 3 for the compounds for which the temperature-dependence of these parameters has been studied. It can be seen that, within the limits of experimental error, $\Delta C^{\ddagger}/\Delta S^{\ddagger}$ is independent of the nature of the substrate, in agreement with the earlier prediction.[3b]

This prediction was based on the assumption that the entropy and heat capacity of activation in S_N1 reactions are almost entirely controlled by the increase in solvation associated with passage into the more polar transition state. This view is not supported by Robertson and his co-workers for solvolysis in water.[13,15] Most of the reactions considered by these workers occur by the bimolecular mechanism, but their analysis of the contributions to $\Delta S^{\ddagger}$ and $\Delta C^{\ddagger}$ which arise from interactions between the solvent and the initial and transition states suggests that $\Delta C^{\ddagger}/\Delta S^{\ddagger}$ should depend on the structure of the substrate for all nucleophilic substitution reactions, contrary to the present observations. It may well be that the factors controlling the magnitude of $\Delta C^{\ddagger}$ and $\Delta S^{\ddagger}$ are not the same in water as in aqueous acetone where one of the solvent components can " solvate " an organic substrate. For example, the entropy of activation for the hydrolysis of t-butyl chloride in water decreases rapidly when small amounts of acetone are added to the solvent,[2a] although the partial molar entropy of water changes little under these conditions; this can be readily demonstrated by combining Ewert's vapour-pressure data [16] with the results of Kister and Waldmann's thermal measurements.[17] A detailed discussion of this point is deferred till current work on solvolysis in other acetone–water mixtures has been completed, but the results already available show that the ratio $\Delta C^{\ddagger}/\Delta S^{\ddagger}$ for S_N1 reactions in such mixtures depends only on the solvent and the temperature, for both chlorides and bromides.

Experimental

Preparation of Materials.—*p*-Nitrodiphenylmethane was prepared by Friedel–Crafts reaction between *p*-nitrobenzyl chloride and benzene,[18] and converted into *p*-nitrodiphenylmethyl bromide by reaction with *N*-bromosuccinimide in carbon tetrachloride in the presence of a small quantity of benzoyl peroxide.[19] The bromide was hydrolysed by refluxing it with aqueous acetone, and the alcohol obtained after removal of the acetone and extraction of the residue with ether. It was purified by recrystallisation from petroleum (b. p. 80—100°) and had m. p. 73—74° (uncorr.). A sample prepared by Meerwein–Ponndorf reduction of *p*-nitrobenzophenone had the same m. p. and mixed m. p. The pure alcohol was chlorinated for 8 hr. in benzene–ether (8 : 1) in the presence of anhydrous zinc chloride by a stream of dry hydrogen chloride. The solution was washed and dried ($MgSO_4$), and the solvent removed under reduced pressure. Repeated recrystallisation of the residue from light petroleum (b. p. 40—60°) gave *p*-nitrodiphenylmethyl chloride, m. p. 43·5—44·5°. *p*-Methylbenzylidene chloride was obtained by the action of phosphorus pentachloride on *p*-tolualdehyde in light petroleum,[20] and purified by distillation under reduced pressure and recrystallisation from light petroleum; it had m. p. 47·5°. t-Butyl chloride, purified by fractional distillation, had n_D^{18} 1·3865. The acid produced by the complete hydrolysis of these chlorides was never less than 99·3% of the theoretical amount.

Acetone was purified as previously described,[3a] and 50% aqueous acetone was prepared by mixing equal volumes of acetone and water.

Rate Measurements and Calculations.—Rates of hydrolysis were measured by methods similar to those employed in the previous work,[3a] and the " observed " values of energies and entropies of activation were calculated from rate coefficients at adjacent temperatures and

[15] Robertson, *Suomen Kem.*, 1960, **33**, *A*, 44.
[16] Ewert, Thesis, Brussels, 1936.
[17] Kister and Waldmann, *J. Phys. Chem.*, 1958, **62**, 245.
[18] Bayer and Villiger, *Ber.*, 1904, **37**, 605.
[19] Dauben and Layton, *J. Amer. Chem. Soc.*, 1959, **81**, 5404.
[20] Auwers and Keil, *Ber.*, 1903, **36**, 1861.

XUM

assumed to refer to the mean temperature of the interval. The standard error in E is then given by

$$\sigma(E) = \frac{RT_1T_2}{T_2 - T_1}\left[\left(\frac{\sigma_1}{k_1}\right)^2 + \left(\frac{\sigma_2}{k_2}\right)^2\right]^{\frac{1}{2}}$$

where σ is the standard error of k, and the subscripts 1 and 2 refer to the temperatures T_1 and T_2, respectively.[21] The standard error of dE/dT was obtained in one of two ways:

(i) from the " best " straight plot of E against T, then

$$\sigma(dE/dT) = \left[\frac{\sum(E_{obs.} - E_{calc.})^2}{(n-2)\sum\theta^2}\right]^{\frac{1}{2}}$$

where n is the number of determinations, θ the difference between the temperature and the mean temperature for all the determinations, and $E_{calc.}$ the value given by the " best " straight plot of E against T.

(ii) from the standard error in E, whereupon

$$\sigma(dE/dT) = \{\sum[\theta.\sigma(E)]^2\}^{\frac{1}{2}}/\sum\theta^2$$

The value of $\sigma(dE/dT)$ quoted in Table 1 and employed to obtain the errors in the values given in Table 3 was always the larger of the values obtained from (i) and (ii).

The authors are indebted to the Council of the Durham Colleges for the award of Post-graduate studentships (to A. Q. and B. S.) and to the Walsall Education Committee for a maintenance grant (to E. F. B.).

UNIVERSITY SCIENCE LABORATORIES, SOUTH ROAD, DURHAM. [*Received, November 16th,* 1960.]

[21] de Fazio, Purlee, and Taft, *J. Amer. Chem. Soc.*, 1955, **77**, 837.

---

389. *The Isolation and Structure of Gafrinin, a Sesquiterpenoid Lactone from* Geigeria africana.

By J. P. DE VILLIERS.

A new sesquiterpenoid lactone, gafrinin, $C_{17}H_{24}O_5$, has been isolated from *Geigeria africana* Gries. It contains an acetoxy-group, a hydroxy-group, and two double bonds. It is monocyclic and structure (I) is proposed.

THREE crystalline compounds, vermeerin, geigerin, and geigerinin, have been isolated from *Geigeria aspera* Harv.[1,2] and the structures of geigerin [3] and geigerinin [2] have been determined.

A new, slightly bitter, sesquiterpenoid acetoxy-lactone, gafrinin, $C_{17}H_{24}O_5$, has been isolated from *G. africana* Gries., the species of " vermeerbos " responsible for " vermeersiekte " (vomiting disease) among sheep in the N.W. Cape Province. Structure (I) is proposed for gafrinin for the reasons advanced below.

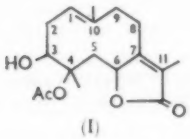
Gafrinin contains a readily reducible trisubstituted double bond (infrared maximum at 813 cm.$^{-1}$). Dihydrogafrinin still shows the ultraviolet absorption of an $\alpha\beta$-unsaturated γ-lactone and must contain a double bond. Gafrinin thus has two double bonds and must be monocyclic, belonging to the group of ten-membered-ring sesquiterpenoid lactones occurring in the Compositæ.[4,5] In common with the other members of this group, cited by Herout, Soucek, and Šorm,[5] gafrinin also gives chamazulene on dehydrogenation.

[1] Rimington and Roets, *Onderstepoort J. Vet. Sci.*, 1936, **7**, 485.
[2] De Villiers, *J.*, 1959, 2412.
[3] Barton and Levisalles, *J.*, 1958, 4518.
[4] Barton and de Mayo, *J.*, 1957, 150.
[5] Herout, Soucek, and Šorm, *Chem. and Ind.*, 1959, 1069.

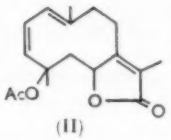
XUM

Structures based on ring systems containing either a six-membered ring or the seven-membered ring of xanthinin [6] are excluded by the impossibility of accommodating the various substituents on such ring systems. The structure of xanthinin type is also eliminated as xanthinin does not give chamazulene on dehydrogenation.

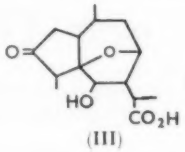
C-Methyl determinations indicate four *C*-methyl groups; therefore, in addition to the acetyl group, there are the usual three *C*-methyl groups in the molecule, and primary oxygen functions and vinylidene groups are excluded. The double bond conjugated to the



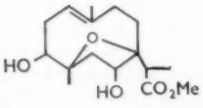
(I)



(II)



(III)



(IV)

lactone must be in the 7,11-position, as in (I). The ultraviolet absorption of dihydrogafrinin ($\lambda_{max.}$ 219 mμ, log ε 3·84) is in agreement with this formulation,[7] as is the resistance of this double bond to hydrogenation. The high absorption of gafrinin at lower wavelength ($\lambda_{max.}$ 205 mμ, log ε 4·05) is due to the additional contribution of the trisubstituted double bond.

Oxidation of dihydrogafrinin with chromium trioxide gave deacetyldehydrodihydrogafrinin, containing a ketone group and a hydroxyl group stable to oxidation. As the hydroxyl group in gafrinin is readily acetylated, it is unlikely to be tertiary, and must thus be the precursor of the ketone group in deacetyldehydrodihydrogafrinin; while the hydroxyl group resistant to oxidation must be formed by the hydrolysis of the acetoxy-group present in gafrinin. Preparation of the 2,4-dinitrophenylhydrazone of this ketone caused elimination of the hydroxyl group; the ultraviolet spectrum of this derivative was in agreement with that of a substituted αβ-unsaturated phenylhydrazone.[8] Deacetyldehydrodihydrogafrinin reduced one mol. of periodate, indicating that the ketone and the hydroxyl groups are vicinal.

On sublimation from alumina in a high vacuum, gafrinin lost one mol. of water, to give anhydrogafrinin (II). The ultraviolet spectrum of this compound ($\lambda_{max.}$ 226 mμ, log ε 4·3) is the sum of the absorptions due to the αβ-unsaturated lactone chromophore ($\lambda_{max.}$ 219 mμ, log ε 3·8) and that of a conjugated diene system ($\lambda_{max.}$ 230 mμ, log ε 4·1). The formation of this diene by dehydration of the hydroxyl group requires the hydroxyl group to be on $C_{(3)}$ and the trisubstituted double bond to be in the 1,10-position.

Treatment of gafrinin with sodium methoxide in dry methanol yielded methyl deacetylgafrinate, which did not show the ultraviolet absorption due to the αβ-unsaturated ester. This was first considered to be due to the formation of a ketone grouping on the site of the hydroxyl group that had been lactonized, but no absorption of such a carbonyl group could be detected in either the ultraviolet or the infrared spectrum. Methyl deacetylgafrinate gave a diacetate which contains no further hydroxyl group. The tertiary hydroxyl group, on the site of the original acetate group in gafrinin, had thus also been lost in the formation of methyl deacetylgafrinate. If the formation of a five-membered-ring ether, similar to that advanced by Barton and Levisalles [3] for allogeigeric acid (III), is postulated, it explains both the disappearance of one hydroxyl group and the change in the ultraviolet spectrum. Methyl deacetylgafrinate thus has structure (IV). It reduced two mol. of periodate, which is in agreement with the behaviour of allogeigeric acid which reduced one mol.[9]

The position of the lactonized hydroxyl group in gafrinin remained to be determined.

[6] Dolejs, Herout, and Šorm, *Coll. Czech. Chem. Comm.*, 1958, **23**, 504.
[7] Büchi and Rosenthal, *J. Amer. Chem. Soc.*, 1956, **78**, 3860.
[8] Braude and Jones, *J.*, 1945, 498.
[9] Perold, *J.*, 1957, 47.

XUM

Methyl deacetylgafrinate has two hydroxyl groups, one at position 3, the other at position 6 or 8. Attempted dehydration of methyl deacetylgafrinate led to the loss of only the 3-hydroxyl group and, although this result confirmed the formation of the diene system postulated for anhydrogafrinin, the failure of methyl deacetylgafrinate to yield, by further dehydration, either a diene and an isolated double bond or a triene did not enable the position of the other hydroxyl group to be established.

Frommodels it was found that methyl deacetylgafrinate would give an isopropylidene derivative only if the remaining hydroxyl group was at position 6. Under the usual conditions methyl deacetylgafrinate readily gave such an isopropylidene derivative, establishing the position of this hydroxyl group as 6. Methyl deacetylgafrinate thus has structure (IV), and gafrinin has structure (I).

Experimental

Ultraviolet spectra were measured for 96% EtOH solutions in a Unicam S.P. 500 spectrophotometer. The infrared spectra were measured in an Infracord spectrophotometer for potassium bromide discs. $[\alpha]_D$ were determined for EtOH solutions. M. p.s are corrected.

Geigeria africana was obtained from the Agricultural Research Station, Koopmansfontein, through the courtesy of the Officer-in-Charge, Mr. J. P. Ebersöhn.

Gafrinin.—Ground, air-dried *G. africana* (17 kg.) was extracted at room temperature, first with hexane, and then twice with 96% ethanol. The ethanol extracts were combined and their volume was reduced to 8 l. An equal volume of water was added, followed by saturated aqueous lead acetate solution (3 l.). After filtration, the excess of lead was removed with potassium dihydrogen phosphate. The clear solution was extracted repeatedly with hexane until no more colour was removed. The alcohol solution was then boiled with charcoal and filtered. The yellow-brown filtrate was diluted with water and extracted with chloroform until colourless. The chloroform extracts were combined and washed with water, and the solvent was removed, giving a viscous brown tar (200 g., 1·2%).

This tar (40 g.) was chromatographed on a column of cellulose powder (2 kg.) impregnated with formamide,[10] with 1 : 1 hexane–benzene as eluant. The chromatogram was controlled by spotting the fractions on paper, impregnating the paper with formamide and developing the spots in hexane–benzene. Fractions, giving a brown spot, R_F 0·19, on being heated at 100° for 3 min. after spraying with the Carr–Price reagent, were combined. After removal of the eluting solvents, the residue was dissolved in chloroform and washed with water, and the chloroform removed by distillation. The residue crystallized from acetone–ether, and recrystallization from the same solvents gave *gafrinin* (2·3 g. from 40 g. of crude extract, 6%) as fine white needles, m. p. 110°, $[\alpha]_D^{28}$ −16·1° (*c* 5·2), $\lambda_{max.}$ 205 mμ (log ε 4·05), $\nu_{max.}$ 3509 (OH), 1751 (αβ-unsaturated γ-lactone), 1701 and 1250 (OAc), and 813 cm.$^{-1}$ (trisubstituted C=C) (Found: C, 66·3; H, 7·9; *C*-Me, 20·1. $C_{17}H_{24}O_5$ requires C, 66·2; H, 7·9; 4*C*-Me, 19·4%).

Gafrinin gave a yellow colour with tetranitromethane, and, on hydrogenation over palladium–calcium carbonate in methanol, absorbed 1·0 mol. of hydrogen, to give *dihydrogafrinin* as an oil, n_D^{20} 1·4981, $[\alpha]_D^{18}$ −10·8° (*c* 4), $\lambda_{max.}$ 219 mμ (log ε 3·84) (Found: C, 65·5; H, 8·8. $C_{17}H_{26}O_5$ requires C, 65·8; H, 8·4%).

With acetic anhydride–perchloric acid, gafrinin gave a yellow oil which was purified by chromatography on acid-washed alumina in ether, followed by distillation, to give *gafrinin acetate*, b. p. 230°/0·5 mm., n_D^{20} 1·5022, $[\alpha]_D^{18}$ +26·5° (*c* 4·4) (Found: C, 65·4; H, 7·5. $C_{19}H_{28}O_6$ requires C, 65·1; H, 7·4%).

Dehydrogenation of Gafrinin.—Dihydrogafrinin (2·5 g.) was dissolved in aqueous potassium hydroxide, and the solution was filtered, then acidified and extracted with chloroform. The solvent was removed by distillation and 30% palladized charcoal (0·75 g.) was added to the residue. After 1 hour's heating at 330° in nitrogen the mixture was extracted with hexane and the heating repeated. The hexane extracts were combined and chromatographed repeatedly on alumina with hexane as eluant, to give an intensely blue oil (35·5 mg.). With 1,3,5-trinitrobenzene, black needles (12 mg.) were obtained, which, on recrystallization from ethanol, had m. p. 132—133° alone or mixed with the chamazulene adduct.

[10] Enslin, Rehm, and Rivett, *J. Sci. Food Agric.*, 1957, **8**, 673.

XUM

Deacetyldehydrodihydrogafrinin.—Dihydrogafrinin (1·2 g.) in acetone was oxidized by the gradual addition of 8N-chromium trioxide in dilute sulphuric acid [11] at room temperature. After dilution with water, the mixture was extracted with ether, and the ether extracts were combined and dried (Na_2SO_4). The residue obtained on removal of the solvent was chromatographed on acid-washed alumina (15 g.) in ether. The first 25 ml. eluted contained most of the material (0·9 g.), which was distilled to give *deacetyldehydrodihydrogafrinin*, b. p. 210°/1 mm., n_D^{20} 1·5009, $[\alpha]_D^{18}$ −14·3° (*c* 4), $\lambda_{max.}$ 219 (log ε 3·8) and 290 mμ (log ε 2·7), $\nu_{max.}$ 3390 (OH), 1748 (γ-lactone) and 1724 cm.$^{-1}$ (medium-ring ketone) (Found: C, 67·5; H, 8·1. $C_{15}H_{22}O_4$ requires C, 67·6; H, 8·3%). It reacted with 2,4-dinitrophenylhydrazine with simultaneous dehydration of the tertiary hydroxyl group, to give *anhydrodeacetyldehydrodihydrogafrinin 2,4-dinitrophenylhydrazone* as red crystals, m. p. 229—230°, $\lambda_{max.}$ (in $CHCl_3$) 255, 305, and 393 mμ (log ε 4·18, 4·17, and 4·52 respectively) (Found: C, 58·3; H, 5·4; N, 12·6. $C_{21}H_{24}N_4O_6$ requires C, 58·9; H, 5·7; N, 13·1%).

Methyl Deacetylgafrinate.—Gafrinin (0·5 g.) was dissolved in dry methanol (50 ml.) containing sodium methoxide (0·2 g.). After 3 days at 4°, the solution was neutralized with solid carbon dioxide and most of the methanol removed under a vacuum. The residue was diluted with water and extracted with chloroform. The chloroform extracts were dried, the solvent was removed, and the residue recrystallized from acetone–ether, to give *methyl deacetylgafrinate* as white crystals (0·35 g.), m. p. 94—95°, $\lambda_{max.}$ 205 mμ (log ε 3·84), $[\alpha]_D^{18}$ −40° (*c* 1) (Found: C, 64·5; H, 8·6. $C_{16}H_{26}O_5$ requires C, 64·4; H, 8·7%).

With acetic anhydride–pyridine, methyl deacetylgafrinin yielded a product which on chromatography on acid-washed alumina in ether gave a clear oil, n_D^{20} 1·4856, which slowly crystallized to give *methyl diacetyldeacetylgafrinate*, m. p. 49·5—50·5°, $[\alpha]_D^{20}$ −62·5° (*c* 3·2) $\lambda_{max.}$ 205 mμ (log ε 3·9) (Found: C, 62·5; H, 8·0. $C_{20}H_{30}O_7$ requires C, 62·8; H, 7·9%).

When shaken with dry acetone and anhydrous copper sulphate for 4 days at 20°, methyl deacetylgafrinin gave the *isopropylidene derivative* as an oil, n_D^{20} 1·4927, $[\alpha]_D^{20}$ −23·2° (*c* 2·8), $\lambda_{max.}$ 203 mμ (log ε 3·7) (Found: C, 67·4; H, 9·1. $C_{19}H_{30}O_5$ requires C, 67·4; H, 8·9%).

Anhydrogafrinin.—Gafrinin (100 mg.), mixed with alumina (200 mg.), was heated at 180°/0·2 mm. During 2 hr. a sublimate (34 mg.) was collected, chiefly as a viscous oil. Crystallization from methanol gave *anhydrogafrinin*, m. p. 55—56°, $\lambda_{max.}$ 226 mμ (log ε 4·3) (Found: C, 70·3; H, 7·7. $C_{17}H_{22}O_4$ requires C, 70·5; H, 7·6%).

Similar treatment of methyl deacetylgafrinin gave *methyl anhydrodeacetylgafrinate* as an oil, n_D^{20} 1·5023, $[\alpha]_D^{20}$ −5·2° (*c* 3·1), $\lambda_{max.}$ 231 mμ (log ε 4·0) (Found: C, 68·6; H, 8·3. $C_{16}H_{24}O_4$ requires C, 68·5; H, 8·6%).

Periodate Oxidations.—Gafrinin, deacetyldehydrodihydrogafrinin, and methyl deacetylgafrinate (50 mg.) were severally dissolved in methanol (1 ml.), 0·2M sodium periodate (2 ml.) was added to each, and the solutions were made up to 5 ml. with water. After 24 hr. the periodate consumed was determined in the usual way. Gafrinin consumed no periodate, deacetyldehydrodihydrogafrinin consumed 1·11 mol., and methyl deacetylgafrinate consumed 2·06 mol.

Mr. D. F. Gouws is thanked for technical assistance and Drs. P. R. Enslin and J. R. Nunn for helpful discussions. The suggestions of the referees, particularly those concerning methyl deacetylgafrinate, are gratefully acknowledged.

Division of Veterinary Services, Department of Agriculture, Onderstepoort, Pretoria.
National Chemical Research Laboratory, South African Council for Scientific and Industrial Research, Pretoria. [*Received, March 14th*, 1960.]

[11] Bowers, Halsall, Jones, and Lemin, *J.*, 1953, 2548.

XUM

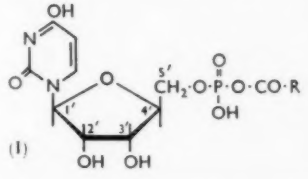
390. *Syntheses of Peptidyl-nucleotidates including* L-*Arginyl*-L-*alanyl*-L-*arginyl*-L-*alanyl Uridine*-5′ *Phosphate.*

By G. Harris and I. C. MacWilliam.

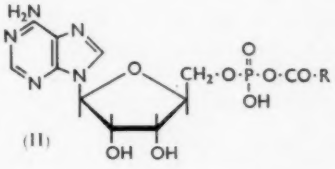
Condensation of various peptides with representative nucleoside-5′ phosphates by means of dicyclohexylcarbodi-imide yields mixed anhydrides of the peptides and nucleotides. Application of this reaction to uridine-5′ phosphate and L-arginyl-L-alanyl-L-arginyl-L-alanine (prepared by condensation of N^{α}-benzyloxycarbonyl-N^{ϵ}-nitro-L-arginyl-L-alanine with N^{ϵ}-nitro-L-arginyl-L-alanine benzyl ester followed by removal of the protecting groups by hydrogenation) gave L-arginyl-L-alanyl-L-arginyl-L-alanyl uridine-5′ phosphate, identical with a product isolated from brewer's yeast.

The existence in brewer's yeast of nucleotide–peptide compounds containing active carboxyl groups (as judged by the formation of peptide hydroxamates) has recently been demonstrated.[1,2,3] One such compound was isolated [3] and shown by degradative studies to be arginyl-alanyl-arginyl-alanyl uridine-5′ phosphate (as I), and in view of the possible importance of materials of this nature as intermediates in protein synthesis the preparation of representative members of the series was undertaken.

Reactions were first carried out by methods already available for the synthesis of the related adenine compounds (II; R = amino-acid residue). For instance, application of Berg's method,[4] as modified by Kingdon, Webster, and Davie,[5] to condensation of adenosine-5′ phosphate with L-leucylglycine by means of dicyclohexylcarbodi-imide



(I)



(II)

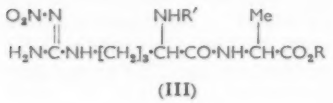
yielded a nucleotide–peptide anhydride (II; R = CH_2·NH·CO·CHBu^i·NH_2) in small yield. The same product was obtained in rather better, though still small, yield by condensing adenosine-5′ phosphate with the protected dipeptide, *N*-(benzylthio)carbonyl-leucylglycine, in the same way and then removing the protecting group with ice-cold perbenzoic acid:[6] In the same manner the corresponding uridine derivative (I) was obtained and the reaction was extended to the tripeptide leucylglycylglycine to yield both compounds (I) and (II). Further, the dipeptide, L-arginyl-L-alanine,[7] closely related to the tetrapeptide obtained by degradation of the natural peptide–nucleotide anhydride of yeast, was readily condensed with uridine-5′ phosphate.

All the peptide–nucleotide anhydrides (I and II) prepared gave a characteristic red colour with ninhydrin reagent on paper and a strong red-brown colour due to the formation of a ferric hydroxamate on treatment with hydroxylamine followed by ferric chloride under controlled conditions (cf. ref. 8). The products of degradation of the leucylglycine derivatives (I and II) and the arginylalanine derivative (I) by hydroxylamine were (*a*) the peptide portion bearing the hydroxamate group and (*b*) the respective nucleotides.

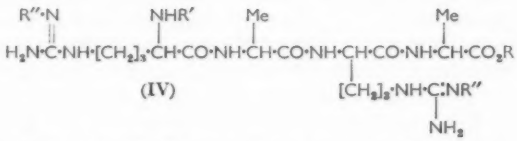
[1] Harris, Davies, and Parsons, *Nature*, 1958, **182**, 1565.
[2] Harris and Davies, *Nature*, 1959, **184**, 788.
[3] Davies and Harris, *Proc. Roy. Soc.*, 1960, *B*, **151**, 537.
[4] Berg, *Fed. Proc.*, 1957, **16**, 151; *J. Biol. Chem.*, 1958, **233**, 608.
[5] Kingdon, Webster, and Davie, *Proc. Nat. Acad. Sci. U.S.A.*, 1958, **44**, 757.
[6] McCorquodale and Mueller, *Arch. Biochem. Biophys.*, 1958, **77**, 13.
[7] Hofmann, Peckham, and Rheiner, *J. Amer. Chem. Soc.*, 1956, **78**, 238.
[8] Koningsberger, van der Grinten, and Overbeek, *Biochim. Biophys. Acta*, 1957, **26**, 483.

Analysis of the anhydrides by complete hydrolysis showed them to contain equimolar proportions of nucleotide and amino-acids. As, moreover, they bore a net positive charge at pH 4·0, migrating towards the cathode like the simple amino-acyl adenosine phosphates on electrophoresis at this pH, had ultraviolet absorption of the same type as the corresponding nucleotides, and reacted with periodate through the *cis*-2′- and 3′-hydroxyl groups,[9] it follows that they have the structures shown. The 3′-phosphates of adenosine and uridine also condensed with peptides to give analogous phosphoric amino-acyl anhydrides which, however, failed to react with periodate.

With this experience the synthesis of the tetrapeptide compound mentioned above was undertaken. The parent tetrapeptide had not previously been prepared.[10] The precursor, arginylalanine, had been prepared[7] from N^{α}-benzyloxycarbonyl-N^{ϵ}-nitro-L-arginyl-L-alanine methyl ester (III; R = Me, R′ = CO·O·CH_2Ph), but in the present work the more readily accessible benzyl ester (III; R = CH_2Ph, R′ = CO·O·CH_2Ph) was preferred. Condensing L-alanine benzyl ester with N^{α}-benzyloxycarbonyl-N^{ϵ}-nitro-



(III)



(IV)

L-arginine[11] by means of dicyclohexylcarbodi-imide[12] gave the new ester (III; R = CH_2Ph, R′ = CO·O·CH_2Ph) in better yield than was given by the mixed anhydride method.[7] After hydrolysis of the ester group by alkali the benzyloxycarbonyl group was smoothly and selectively removed by treatment with dry hydrogen chloride in carbon tetrachloride,[11] to give N^{ϵ}-nitro-L-arginyl-L-alanine benzyl ester (III; R = R′ = H). Combination of the acid (III; R = H, R′ = CO·O·CH_2Ph) with the ester (III; R = CH_2Ph, R′ = H) by means of dicyclohexylcarbodi-imide afforded crystalline N^{α}-benzyloxycarbonyl-N^{ϵ}-nitro-L-arginyl-L-alanyl-N^{ϵ}-nitro-L-arginyl-L-alanine benzyl ester (IV; R = H, R′ = CO·O·CH_2Ph, R″ = NO_2) and thence by hydrogenation the required tetrapeptide (IV; R = R′ = R″ = H). Direct condensation of this tetrapeptide with uridine-5′ phosphate as in the reactions above (cf. ref. 4) gave a complex mixture from which a compound was isolated having properties identical with those of the naturally occurring material from brewer's yeast.[3]

Experimental

Adenine-5′ L-Leucylglycyl Phosphate.—(*a*) Adenosine-5′ phosphate (190 mg.) and L-leucylglycine (1·04 g.) were dissolved in a mixture of N-hydrochloric acid (5·5 ml.), pyridine (44 ml.), and water (7·6 ml.) at 0°, and dicyclohexylcarbodi-imide (2·0 g.) was added with stirring. The mixture was kept for 3 hr. at 0°, then ice-cold acetone (500 ml.) was added. The precipitate was immediately filtered off, dried for 1 hr. in a vacuum, and extracted with 0·1M-acetate buffer at pH 5·0 (10 ml.). The extract was evaporated in a vacuum at room temperature. The residue was dissolved in a small amount of water and placed on two Whatman 3MM papers, each 10 cm. wide, for electrophoresis in acetate buffer at pH 4·0 with a voltage gradient of 10—15 v/cm. overnight. The material which combined the properties of reacting with hydroxylamine to form a hydroxamate,[8] giving a red colour with ninhydrin reagent, and migrating towards the cathode, as located by guide strips, was eluted from the papers by means of cold water, and the solution was dried lyophilically. The resulting solid was dissolved in a little water and chromatographed on Whatman 3MM paper in butanol–acetic acid–water (4 : 1 : 1). The required material was located by its reactions with hydroxylamine and ninhydrin in a band

[9] Dixon and Lipkin, *Analyt. Chem.*, 1954, **26**, 1092.
[10] Goodman and Kenner, *Adv. Protein Chem.*, 1957, **12**, 466.
[11] Katchalsky and Paecht, *J. Amer. Chem. Soc.*, 1954, **76**, 6042.
[12] Sheehan, Goodman, and Hess, *J. Amer. Chem. Soc.*, 1956, **78**, 1367.

having R_F 0·27 in the above solvent and R_F 0·20 in ethyl acetate–propan-1-ol–water (2 : 7 : 1) (containing 5 ml. of acetic acid per l. to prevent decomposition of the product). It was eluted by means of cold water, and the solution was freeze-dried.

(*b*) Adenosine-5′ phosphate (30 mg.) and *N*-(benzylthio)carbonyl-DL-leucylglycine (135 mg., see below) were dissolved in pyridine (4·2 ml.) and water (0·45 ml.) at 0°, whereafter dicyclohexylcarbodi-imide (1·8 g.) was added. The mixture was cooled to −10° and kept for 1 hr. Ether (30 ml.) was added and the precipitate collected and dried in a vacuum. It was then extracted with 0·01N-hydrochloric acid (1 × 10 ml.; 2 × 5 ml.), and the solution was treated at 0° with perbenzoic acid (100 mg.) in water (12 ml.) and kept at 0° for 20 min. The mixture was extracted with cold chloroform, and the aqueous phase freeze-dried. Further working up by electrophoresis and chromatography was effected as under (*a*).

Analysis of the product was carried out as described in detail [8] for the nucleotide–peptide compound from yeast. The molar ratios found were adenosine-5′ phosphate : leucine : glycine = 1·0 : 1·3 : 1·0.

DL-*Leucylglycyl Uridine-5′ Phosphate*.—Uridine-5′ phosphate (30 mg.) and *N*-(benzylthio)-carbonyl-DL-leucylglycine (135 mg.) in pyridine (4·2 ml.) and water (0·28 ml.) were condensed as above by means of dicyclohexylcarbodi-imide (1·8 g.), and the product, presumably consisting of a mixture of diastereoisomers, was worked up as for the corresponding adenosine compound. Analysis of the product gave the molar ratios uridine-5′ phosphate : leucine : glycine = 0·92 : 1·0 : 0·80.

Similar condensations with DL-leucylglycylglycine and its *N*-(benzylthio)carbonyl derivative (see below) together with either adenosine-5′ or uridine-5′ phosphate gave analogous products; uridine-5′ phosphate reacted with glycine or leucine to give the respective amino-acid derivatives. Degradation with hydroxylamine and characterisation of the products was effected as described earlier.[8]

N-(*Benzylthio*)*carbonylglycine*.—Glycine (0·6 g.) and sodium hydrogen carbonate (1·68 g.) in water (12 ml.) at 0° were treated dropwise with stirring with *S*-benzylthioformyl chloride [12] (1·1 ml.) in dioxan (8 ml.). After 1 hr. the mixture was acidified with 5N-hydrochloric acid, concentrated, and kept at 0°. The product separated as plates, m. p. 135—136° (Found: N, 6·0; S, 14·3. Calc. for $C_{10}H_{11}NO_3S$: N, 6·2; S, 14·2%). McCorquodale and Mueller [6] give m. p. 153·5° for needles, presumably polymorphic with the product described here.

N-(*Benzylthio*)*carbonyl*-DL-*leucylglycine*.—DL-Leucylglycine (5·0 g.) and sodium hydrogen carbonate (6·1 g.) in water (70 ml.) were treated, as above, with *S*-benzylthioformyl chloride (5·6 g.). The upper oily layer was separated and the aqueous solution extracted with ether, after which the clear aqueous layer was acidified to pH 2 and kept at 0° overnight after seeding. The *product* (5·0 g.) (m. p. 175—176°), together with a further crop (0·25 g.) from the mother-liquor, recrystallised from ethanol as needles, m. p. 177° (Found: C, 56·4; H, 6·8; N, 8·4; S, 9·1. $C_{16}H_{22}N_2O_4S$ requires C, 56·8; H, 6·5; N, 8·3; S, 9·5%).

N-(*Benzylthio*)*carbonyl*-L-*leucylglycine*.—This *compound* was obtained in the same manner as the DL-isomer and recrystallised from aqueous ethanol as needles, m. p. 109—111° (Found: N, 7·8. $C_{16}H_{22}N_2O_4S$ requires N, 8·3%).

N-(*Benzylthio*)*carbonyl*-DL-*leucylglycylglycine*.—Prepared by the above procedure, this *peptide* recrystallised from aqueous ethanol as needles, m. p. 148—150° (Found: N, 10·1; S, 7·8. $C_{18}H_{25}N_3O_5S$ requires N, 10·6; S, 8·1%).

N^G-*Nitro*-L-*arginine*.—This was prepared by the method of Hofmann, Peckham, and Rheiner [7] and recrystallised (yield 60%) from hot water. It had m. p. 253—254°, $[\alpha]_D^{20}$ +23° in 2N-HCl (lit.,[7] m. p. 262°, $[\alpha]_D^{22}$ +24·3° in 2N-HCl).

N^{α}-*Benzyloxycarbonyl*-N^G-*nitro*-L-*arginine*.—N^G-Nitro-L-arginine (4·5 g.) was treated with benzyloxyformyl chloride [14] (9 g.). The product, recrystallised from aqueous ethanol (3·8 g., 52%), had m. p. 127—128°, $[\alpha]_D^{27}$ −4° in MeOH (lit., m. p. 134—136°, $[\alpha]_D^{27}$ −3·5° in MeOH,[7] m. p. 126° [14]).

L-*Alanine Benzyl Ester*.—The hydrochloride was obtained [15] as needles (78%) from methanol–ether. It had m. p. 137—138°, $[\alpha]_D^{23}$ −13° in MeOH (Erlanger and Hall [15] give m. p. 140°, $[\alpha]_D$ −14·8°). The free base was prepared by dissolving the hydrochloride in water, adjusting the pH of the solution to 9 with sodium carbonate solution, extracting the mixture with ether,

[13] Kollonitsch, Gabor, and Hajos, *Chem. Ber.*, 1956, **89**, 2293.
[14] Bergmann, Zervas, and Rinke, *Z. physiol. Chem.*, 1934, **224**, 40.
[15] Erlanger and Hall, *J. Amer. Chem. Soc*, 1954, **76**, 5781.

XUM

evaporating the ether layer to dryness, and dissolving the residual syrup in tetrahydropyran (see below).

N^{α}-*Benzyloxycarbonyl*-N^{ϵ}-*nitro*-L-*arginyl*-L-*alanine Benzyl Ester* (III; R = CH_2Ph, R′ = $CO{\cdot}O{\cdot}CH_2Ph$).—The preceding ester (1·70 g.) in tetrahydropyran (20 ml.) was mixed with N^{α}-benzyloxycarbonyl-N^{ϵ}-nitro-L-arginine (1·29 g.) in the same solvent (10 ml.). Dicyclohexylcarbodi-imide (1·0 g.) was added and the mixture shaken at room temperature for 5 hr. and kept overnight at 0°. Acetic acid (1 ml.) was added, the mixture shaken and left aside for 0·5 hr., and the precipitate of dicyclohexylurea filtered off and washed with ethyl acetate. The solvent was removed from the filtrate and the resulting residue redissolved in ethyl acetate (100 ml.), washed successively with N-hydrochloric acid, water, N-sodium hydrogen carbonate, and water, and dried (Na_2SO_4). The *peptide* (2·0 g., 81%) crystallised from aqueous ethanol as plates, m. p. 163°, $[\alpha]_D$ −11° in MeOH (Found: C, 55·7; H, 6·0; N, 16·1. $C_{24}H_{30}N_6O_7$ requires C, 56·0; H, 5·8; N, 16·3%).

N^{α}-*Benzyloxycarbonyl*-N^{ϵ}-*nitro*-L-*arginyl*-L-*alanine* (III; R = H, R′ = $CO{\cdot}O{\cdot}CH_2{\cdot}Ph$).—The preceding dipeptide ester (0·8 g.) was shaken with 0·5N-sodium hydroxide (10 ml.) for 1 hr. at room temperature, and the solution was then neutralised with hydrochloric acid and extracted with ethyl acetate (3 × 50 ml.). The extracts were washed with water (2 × 25 ml.), dried, and evaporated to dryness. The residue crystallised from aqueous ethanol (0·59 g., 88%) and had m. p. 206—207°, $[\alpha]_D^{20}$ −4° in pyridine (Hofmann *et al.*[7] give m. p. 207—208°, $[\alpha]_D^{20}$ −5·9°) (Found: N, 22·7. Calc. for $C_{11}H_{23}N_5O_5$: N, 22·9%).

L-*Arginyl*-L-*alanine* (III; R = R′ = H). L-Alanine benzyl ester (0·2 g.) in methanol containing 10% of acetic acid was hydrogenated over 10% palladium–charcoal as described by Hofmann *et al.*[7] After removal of the catalyst and solvents the dipeptide was isolated as the acetate and was recrystallised from aqueous ethanol. It had m. p. 170—171°, $[\alpha]_D^{20}$ +7·8°. Hofmann *et al.*[7] found m. p. 173—174°, $[\alpha]_D^{23}$ +9·7° in H_2O.

L-*Arginyl*-L-*alanyl Uridine*-5′ *Phosphate*.—L-Arginyl-L-alanine (60 mg.) and uridine-5′ phosphate (52 mg.) were dissolved in water (1·2 ml.), N-hydrochloric acid (0·8 ml.), and pyridine (8 ml.) and cooled to 0°. Dicyclohexylcarbodi-imide (300 mg.) in pyridine (4 ml.) was added and the mixture was treated as described above for L-leucylglycyl adenosine-5′ phosphate. After separation from unchanged uridine-5′ phosphate by electrophoresis on paper, the product was isolate by freeze-drying, as a glass (40 mg.). It migrated to the cathode during electrophoresis in acetate buffer at pH 4 and with hydroxylamine gave a hydroxamate.[8] The following molar ratios were found: uracil : ribose : phosphate : arginine : alanine = 1·18 : 1·02 : 1·0 : 0·85 : 0·92. With sodium metaperiodate under our usual conditions[9] immediate uptake of the reagent was observed.

N^{ϵ}-*Nitro*-L-*arginyl*-L-*alanine Benzyl Ester* (III; R = CH_2Ph, R′ = H).—N^{α}-Benzyloxycarbonyl-N^{ϵ}-nitro-L-arginyl-L-alanine benzyl ester (0·5 g.) was dissolved in carbon tetrachloride (20 ml.), and dry hydrogen chloride was passed through the solution for 0·5 hr. The solution was then poured into dry ether (100 ml.) to precipitate the *product* as hydrochloride. This separated from methanol–ether as needles (0·25 g., 61%), m. p. 171—173°, $[\alpha]_D$ −10° in MeOH (Found: C, 46·6; H, 5·5; N, 20·1. $C_{16}H_{25}ClN_6O_5$ requires C, 46·2; H, 5·8; N, 20·2%).

N^{α}-*Benzyloxycarbonyl*-N^{ϵ}-*nitro*-L-*arginyl*-L-*alanyl*-N^{ϵ}-*nitro*-L-*arginyl*-L-*alanine Benzyl Ester* (IV; R = CH_2Ph, R′ = $CO{\cdot}O{\cdot}CH_2Ph$, R″ = NO_2).—N^{α}-Benzyloxycarbonyl-N^{ϵ}-nitro-L-arginyl-L-alanine (0·21 g.) and the preceding ester (0·19 g.) in tetrahydropyran (10 ml.) were shaken for 5 hr. with dicyclohexylcarbodi-imide (0·2 g.) and treated as above. The *tetrapeptide ester* separated from aqueous ethanol as plates (0·31 g., 79%), m. p. 212—213°, $[\alpha]_D^{19}$ −5·6° in MeOH (Found: C, 50·7; H, 5·8; N, 20·9. $C_{33}H_{46}N_{12}O_{11}$ requires C, 50·4; H, 5·9; N, 21·4%).

L-*Arginyl*-L-*alanyl*-L-*arginyl*-L-*alanine* (IV; R = R′ = R″ = H).—The last-mentioned product (0·2 g.) was hydrogenated as described above for L-arginyl-L-alanine. The solvent was removed by evaporation to leave the free *tetrapeptide* as an amorphous powder (0·11 g., 81%), $[\alpha]_D$ +7·8° in H_2O (Found: C, 45·1; H, 7·5; N, 24·1. $C_{18}H_{36}N_{10}O_5{,}2CH_3{\cdot}CO_2H$ requires C, 44·6; H, 7·5; N, 23·7%).

L-*Arginyl*-L-*alanyl*-L-*arginyl*-L-*alanyl Uridine*-5′ *Phosphate*.—The above free tetrapeptide (56 mg.) in N-hydrochloric acid (0·5 ml.) was mixed with uridine-5′ phosphate (26 mg.) in water (0·5 ml.) and pyridine (5 ml.) and cooled to 0°. Dicyclohexylcarbodi-imide (0·2 g.) in pyridine (1 ml.) was added. The mixture was treated as described for L-leucylglycyl adenosine-5′ phosphate and then subjected to electrophoresis in acetate buffer at pH 4 for 4 hr. at 10 mA (see above). A zone on the electrophoregram containing materia which migrated *ca.* 2 cm.

XUM

towards the cathode and with hydroxylamine formed a product yielding a ferric salt was separated and eluted from the papers with 50% aqueous ethanol. After removal of the solvent under reduced pressure at 10°, a glass (10 mg.), $[\alpha]_D$ +11·2° in H_2O, was obtained which analysis [2] showed to contain uracil, ribose, phosphate, arginine, and alanine in the ratio 1·0 : 0·9 : 1·1 : 1·9 : 1·8. The material behaved as a homogeneous substance when subjected to electrophoresis as above or to chromatography in acidic solvents [butanol–acetic acid–water (4 : 1 : 1); acetone–30% acetic acid (1 : 1); [16] or ethyl acetate–propan-1-ol–water (2 : 7 : 1)], and had the same mobilities as the natural material. Treatment with aminopeptidase gave the products [3] obtained also from the natural compound.

The authors thank Dr. A. H. Cook, F.R.S., for his advice and encouragement throughout the investigation.

BREWING INDUSTRY RESEARCH FOUNDATION,
NUTFIELD, SURREY. [*Received, April 4th,* 1960.]

[16] Davies and Harris, *Biochim. Biophys. Acta*, 1961, **45**, 39.

---

391. *The Polymerization of 3-Substituted Oxazolidine-2,5-diones.*

By C. H. BAMFORD, H. BLOCK, and A. C. P. PUGH.

The tertiary amine-catalysed polymerization of sarcosine-*N*-carboxy-anhydride in the presence of 3-methylhydantoin has been shown to be similar to the catalysis by lithium chloride reported previously. Use of 3-phenyloxazolidine-2,5-dione as the cyclic anhydride has permitted isolation and characterization of 3-methyl-1-*N*-phenylglycylhydantoin as the product from both these reactions. The isolation of this compound, which is a stable member of a family of generally reactive kinetic intermediates, indicates the nature of the paths in these reactions, and, by analogy, the nature of the reaction paths in the polymerization, catalysed by tertiary amines or lithium chloride, of oxazolidine-2,5-diones unsubstituted in the 3-position. A generalized reaction scheme for the polymerization of oxazolidine-2,5-diones is given.

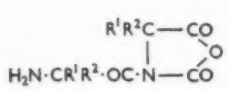
THE mechanism of the polymerization of oxazolidine-2,5-diones catalysed by tertiary bases and by lithium chloride has been discussed in earlier papers.[1a,b] It has been suggested that both reactions proceed through the formation of a bifunctional intermediate of type (I) which cannot occur with a 3-substituted oxazolidine-2,5-dione. There is abundant experimental evidence [1a,b,2a,b,3] that polymerization of sarcosine-*N*-carboxy-anhydride is not induced by tertiary bases. Apparent indications to the contrary such as the observations by Bilek *et al.*[4] (recently cited again by Katchalsky and Sela [5]) can almost certainly be attributed to the presence of small quantities of active impurities, particularly water. L-Proline-*N*-carboxy-anhydride, which we show to be extremely sensitive to traces of impurities, has given far more varied results in its ability to be polymerized by tertiary bases. However, under the most rigorous and testing conditions only low rates of polymerization are observed.

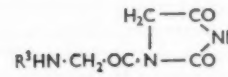
Although sarcosine-*N*-carboxy-anhydride is not polymerized by lithium chloride alone, polymerization does occur in the presence of 3-methylhydantoin. It has been suggested that an intermediate (II) is involved,[1a] with structure analogous to (I). That 1,3-dimethylhydantoin does not produce any reaction is consistent with this.[2a] In view

[1] (*a*) Ballard, Bamford, and Weymouth, *Proc. Roy. Soc.*, 1955, *A*, **227**, 155; (*b*) Ballard and Bamford, *J.*, 1956, 381; (*c*) Ballard, Bamford, and Elliott, *Makromol. Chem.*, 1960, **35**, 222; (*d*) Ballard and Bamford, *Proc. Roy. Soc.*, 1954, *A*, **223**, 495; (*e*) Ballard and Bamford, *J.*, 1958, 355.
[2] (*a*) Bamford, *Chem. Soc. Special Publ.* No. 2, 1955, p. 45; (*b*) Schlögl, *ibid.*, p. 47.
[3] Hargitay and Buyle, personal communication.
[4] Bilek, Derkosch, Michl, and Wessely, *Monatsh.*, 1953, **84**, 717.
[5] Katchalski and Sela, *Adv. Protein Chem.*, 1958, **13**, 243.

XUM

of the similarity of the hydantoin and oxazolidine-2,5-dione rings it was therefore natural to suppose that the polymerization of oxazolidine-2,5-diones which are not *N*-substituted proceeds through (II) and resembles that initiated by tertiary bases.[1a]

(I) 

 (II)

In the present paper we complete the analogy by showing that sarcosine-*N*-carboxy-anhydride polymerizes readily in the presence of a tertiary base if 3-methylhydantoin is added. Further, we establish unequivocally the existence of intermediates of type (II) by the isolation of 3-methyl-1-*N*-phenylglycylhydantoin (II; $R^3 = Ph$) from reaction mixtures containing 3-methylhydantoin and 3-phenyloxazolidine-2,5-dione together with a tertiary base or lithium chloride. Such intermediates are not formed in the presence of primary bases. These observations support the mechanism which we have previously proposed, and we show later that the essentials of this mechanism are consistent with all the available observations. The reactions of primary, secondary, and tertiary bases with oxazolidine-2,5-diones can now be fitted into a self-consistent scheme.

Experimental

Materials.—Sarcosine-*N*-carboxy-anhydride, prepared by the method of Hanby *et al.*,[6] was purified as described by Ballard *et al.*[1a]

L-Proline-*N*-carboxy-anhydride, kindly supplied by Mr. A. A. Randall of this laboratory, was sublimed at 35—40°/10^{-4} mm. immediately before use.

3-Phenyloxazolidine-2,5-dione [7] was recrystallized from ethyl acetate–light petroleum (b. p. 60—80°) and was sublimed at 100—110°/10^{-4} mm. immediately before use.

3-Methylhydantoin [8] was twice recrystallized from ethanol and was sublimed at 150°/10^{-4} mm. before use.

Triethylamine, from Judex Co., Ltd., was treated with acetic anhydride (10% v/v) for 0·5 hr. The triethylamine was distilled off at 89—90°, left over solid sodium hydroxide for 12 hr., and redistilled.

Tributylamine, from Eastman-Kodak Corp., was treated with acetic anhydride (10% v/v) for 0·5 hr. The anhydride was distilled off and the tributylamine distilled at *ca.* 10 mm. After drying (NaOH; 12 hr.) the product was redistilled at *ca.* 10 mm.

Lithium chloride, from May and Baker Ltd., was used without purification. It was dried as described below.

Hexylamine, from L. Light & Co., Ltd., was dried (NaOH) and fractionated under reduced pressure.

NN-Dimethylformamide, from Honeywill & Stein Ltd., was dried (P_2O_5) and fractionated at 25° under reduced pressure, the middle fraction being collected. Repetition of this procedure resulted in a pure and dry sample as shown by its inability to cause measurable polymerization of sarcosine-*N*-carboxy-anhydride over a substantial period.

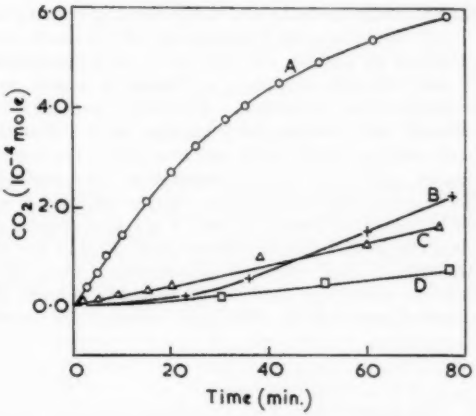
All materials, after purification were not allowed to come into contact with the air except in a dry box.

Results.—(a) *System: sarcosine-N-carboxy-anhydride, 3-methylhydantoin, tertiary base.* Kinetic experiments were carried out in a two-limbed vessel in which, before the experiment, the anhydride and other reagents were kept in separate limbs. The reaction vessel was connected to a constant-volume manometric system [1d] by means of a tapered joint, and rotation of the vessel about the joint resulted in the mixing of the reactants and in the start of the polymerization. Mixtures were shaken in a thermostat bath at 25·0°. The results are shown in the Figure.

[6] Hanby, Waley, and Watson, *J.*, 1950, 3009.
[7] Fuchs, *Ber.*, 1922, **55**, 2943.
[8] Siemonson, *Annalen*, 1904, **333**, 113.

An intermediate (II; R^3 = Me) was sought from triethylamine, 3-methylhydantoin, and sarcosine-*N*-carboxy-anhydride in the molar ratios 100 : 10 : 1 but only polysarcosine was isolated.

(b) *System: L-proline-N-carboxy-anhydride, tertiary base.* Polymerization was markedly slower in the system L-proline-*N*-carboxy-anhydride, tributylamine in *NN*-dimethylformamide (Figure) if reagents were freshly distilled and dried by azeotropic distillation with benzene.



Conversion–time curves for reactions of oxazolidine-2,5-diones with tributylamine in NN-*dimethylformamide at* 25°.

Concns. (mole/l.): sarcosine-*N*-carboxy-anhydride, (A) 0·332, (B) 0·317, (D) 0·289; 3-methylhydantoin, (A), 0·178, (B) 0·185, (D) 0; tributylamine, (A) 0·042, (B) 0, (D) 0·262. Curve C is for L-proline-*N*-carboxy-anhydride (0·291) and tributylamine (0·129 mole/l.).

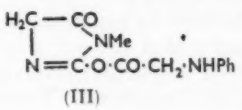
Complete conversion for 0·332 mole/l. of sarcosine-*N*-carboxy-anhydride yields 10^{-2} mole of CO_2.

In the absence of such precautions results were very varied; in one instance polymerization was complete in 8 min.

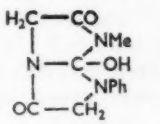
(c) *Isolation and characterization of intermediates of type* (II), *with base-catalysis.* Reaction occurred when tributylamine was added to a solution of 3-phenyloxazolidine-2,5-dione and 3-methylhydantoin in *NN*-dimethylformamide. The carbon dioxide evolved was frozen out at −196°; a yield of 96% was estimated by measuring the pressure in a vessel of known volume and temperature.

A solution of 3-phenyloxazolidine-2,5-dione (3 g.), 3-methylhydantoin (2 g.), and triethylamine (20 ml.) in *NN*-dimethylformamide (30 ml.) was concentrated after 2 hr. at reduced pressure to *ca.* 50 ml.; it deposited crystalline 3-*methyl*-1-*N*-*phenylglycylhydantoin* (II; R^3 = Ph) (2·2 g.), m. p. 227—228° (from benzene) (Found: C, 58·1; H, 5·3; N, 16·5. $C_{12}H_{13}N_3O_3$ requires C, 58·3; H, 5·3; N, 17·0%).

This compound (0·1 g.) was hydrolysed for 0·5 hr. in refluxing 2N-sodium hydroxide (5 ml.). Paper chromatography with butanol–pyridine–water for development, and Reindel and Hoppe's technique [9] for rendering the spots visible, with a control 1 : 1 mixture of *N*-phenylglycine and 3-methylhydantoin in 2N-sodium hydroxide at the concentrations expected from the hydrolysis, showed these materials to be the hydrolysis products.



(III)



(IV)

The infrared spectrum of compound (II; R^3 = Ph), in a potassium chloride disc, recorded on a Perkin-Elmer Infracord spectrophotometer, showed absence of the ester doublet in the region 1000—1200 $cm.^{-1}$, thus eliminating structure (III) for this compound.

Compound (II; R^3 = Ph) (0·2 g.) was refluxed in acetyl chloride (10 ml.) for 1½ hr. The *acetyl derivative* separated; recrystallized from chloroform–light petroleum (b. p. 60—80°), it (0·15 g.) had m. p. 230° (Found: C, 58·0; H, 5·5; N, 14·4. $C_{14}H_{15}N_3O_4$ requires C, 58·1; H, 5·2; N, 14·5%). Formation of this derivative is strong evidence against structure (IV) (tertiary

[9] Reindel and Hoppe, *Chem. Ber.*, 1954, **87**, 1103.

XUM

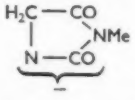
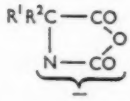
alcohol). The infrared spectrum (KCl disc) supports this conclusion since the absence of the ester doublet in the region 1000—1200 cm.$^{-1}$ eliminates ester formation.

(d) *System: hexylamine, 3-phenyloxazolidine-2,5-dione, 3-methylhydantoin.* 3-Phenyloxazolidine-2,5-dione (2 g.), 3-methylhydantoin (1·3 g.), and hexylamine (1·2 g.) in *NN*-dimethylformamide (25 ml.) were allowed to react for 12 hr. Precipitation with ice-water resulted in a solid (presumably the hexylamide) which was extremely soluble in ether. The fact that 3-methyl-1-*N*-phenylglycylhydantoin is only sparingly soluble in this solvent showed that this intermediate was not present in concentrations greater than 1%.

(e) *Isolation of an intermediate* (II) *in reaction with catalysis by lithium chloride.* Reaction catalysed by lithium chloride between 3-phenyloxazolidine-2,5-dione and 3-methylhydantoin is very strongly inhibited by traces of water, so the reagents were dried by removing the benzene–water azeotrope. 3-Methylhydantoin (0·6 g.) and lithium chloride (0·3 g.) were refluxed with sodium-dried benzene in *NN*-dimethylformamide (30 ml.) under a Dean–Stark head until no more water was removed. During the drying, the *NN*-dimethylformamide was heated, and since slight decomposition to dimethylamine under these conditions was possible, the solvents were removed on a water-bath under reduced pressure and finally at 100°/10^{-4} mm. 3-Phenyloxazolidine-2,5-dione (1 g.) was similarly dried. The three compounds were then dissolved in *NN*-dimethylformamide (30 ml.) and left for 12 hr., carbon dioxide being evolved. Addition to ice afforded 3-methyl-1-*N*-phenylglycylhydantoin which, recrystallized from benzene, had m. p. 226° (0·5 g.) (Found: C, 58·2; H, 5·5; N, 16·6%) and an infrared spectrum identical with that of the sample prepared as described in (c) above.

Discussion

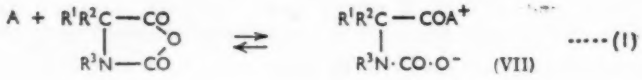
The results shown in the Figure confirm previous observations that the initial rate of reaction of sarcosine-*N*-carboxy-anhydride in the presence of tertiary base or of 3-methylhydantoin is of the same low order as the rate of decomposition of sarcosine-*N*-carboxy-anhydride in pure solvent. When tertiary base and 3-methylhydantoin are both present a much higher rate is observed; therefore, kinetically, tertiary bases behave very similarly to lithium chloride [1a] in these systems. The parallelism is emphasized by the isolation of the intermediate (II; $R^3 = Ph$) in both cases. These observations show definitely that the 3-methylhydantoin anion (V) is an intermediate in both reactions, and strongly suggest that with oxazolidine-2,5-diones which are not *N*-substituted the anion (VI) is involved in the corresponding reactions.

(V)   (VI)

The marked variation in the rate of polymerization of L-proline-*N*-carboxy-anhydride when treated with tertiary base, together with the observation that reaction may be slow, indicates that the well-known rapid polymerization of this anhydride by a tertiary base is an impurity effect. The sensitivity of this anhydride to impurities is not unexpected since it is extremely reactive.[1e] We do not consider that the low polymerization rate observed with our purest materials is any proof of a mechanism involving only tertiary base and anhydride since traces of impurities may still be present. This reaction is being investigated further.

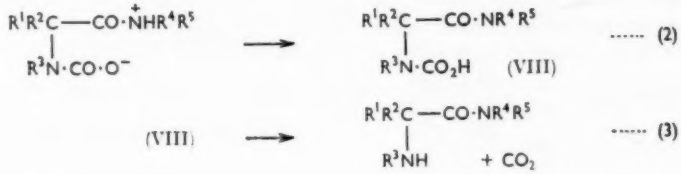
The above and other evidence is consistent with the following mechanisms for polymerization involving initiation by primary base and catalysis by tertiary base and lithium chloride.

(i) A rate-determining (reversible) association between the initiator and the oxazolidine-2,5-dione:

 (VII) ·····(I)

where A represents $R^4R^5R^6N$ or Cl^- and the ion (VII) is an equivalent representation of the mesomeric or tautomeric forms previously described.[1b]

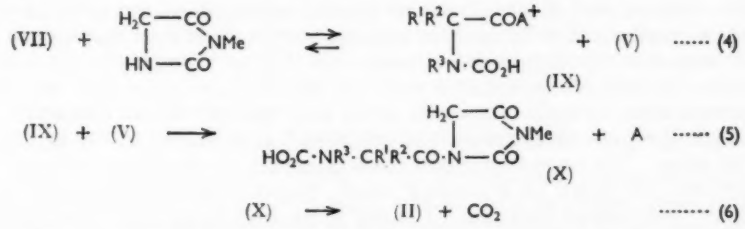
(ii) If A is an amine, and any or all of R^4, R^5, R^6 are hydrogen, proton transfer from A to the *N*-carboxy-anion occurs, followed by decomposition of the unstable carbamic acid (VIII), *e.g.*:



The proton transfer is faster than reactions (4) and (7) described below; hence the reactions described in sections (iv) and (v) do not occur with primary bases. Reactions (1), (2), and (3) describe the normal polymerization initiated by a primary or secondary base.

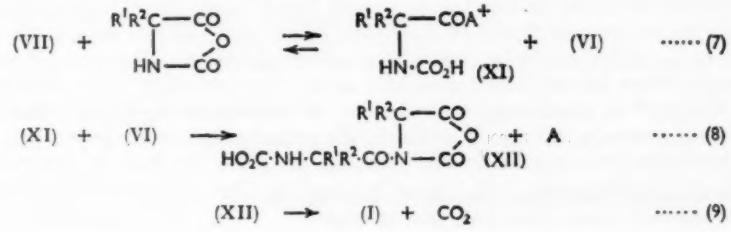
(iii) If A is a tertiary amine or a weakly basic anion such as Cl^- in *NN*-dimethylformamide and R^3 is not hydrogen, no further reaction will occur, and it is presumed that the ion (VII) is in equilibrium with the catalyst and anhydride. This equilibrium is analogous to that between hydantoin and hydantoic acid. In the case of L-proline-*N*-carboxy-anhydride this equilibrium presumably results in higher concentrations of ion (VII) than occur with sarcosine-*N*-carboxy-anhydride or 3-phenyloxazolidine-2,5-dione. Protonating impurities would then cause more rapid polymerization with L-proline-*N*-carboxy-anhydride. That initiation by lithium chloride involves primarily the chloride anion rather than the lithium cation is shown by the fact that lithium perchlorate does not initiate the polymerization of γ-benzyl-L-glutamate-*N*-carboxy-anhydride.[1c]

(iv) If to the equilibrium mixture described in (iii) 3-methylhydantoin is added, reactions (4)—(6) take place. Of these, (5) would be expected to be very fast.



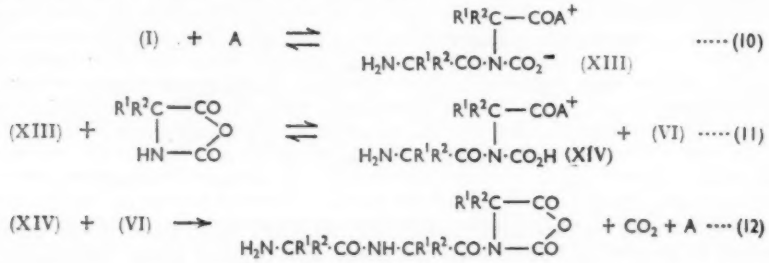
For compound (II; R^3 = Ph) the substituted aniline derivative is too weak a secondary base to enter into further propagation reactions, and it is therefore possible to isolate the intermediate in this case.

(v) If R^3 = H, the intermediate (VII) can react with oxazolidine-2,5-dione as in (7). Reactions (7)—(9) are analogous to reactions (4)—(6).



Further polymerization can now occur (*a*) by the normal primary-base mechanism involving the basic group of compound (I) and either the initial anhydride or the anhydride end of a second molecule (I), or (*b*) by the scheme (vi). In the latter the anhydride portion of compound (I) enters into reactions similar to those in (i) and (v).

(vi)



Reactions (1) and (7)—(9) lead to a mechanism essentially similar to that proposed for initiation by a tertiary base,[1b] while (vi) is an additional mode of propagation from the anhydride end of the bifunctional intermediate.

We believe that the formation of ions (V) and (VI) occurs by reaction of 3-methylhydantoin or oxazolidine-2,5-dione with (VII) rather than with tertiary base, since in this manner a closer similarity in mechanism between primary, secondary, and tertiary bases can be achieved. In the case of lithium chloride there is no such indication of the actual reaction path and ionization of 3-methylhydantoin or oxazolidine-2,5-dione may be the initial step.

The original mechanism for catalysis by a tertiary base proposed by Ballard and Bamford [1b] was criticized by Katchalski and Sela [5] on three counts. The first, that the experimental evidence does not support the idea that tertiary bases cannot initiate the polymerization of *N*-substituted anhydrides, has been shown above to be without foundation. Indeed, the low rate of reaction between tertiary bases and sarcosine- or L-proline-*N*-carboxy-anhydride is inconsistent with the various rapid ionic mechanisms which have been advanced.[5,10] The second criticism was that no experimental evidence for intermediates of type (I) existed and that "it may be anticipated that the isolation and characterization of such compounds could be achieved without difficulty." However, the experimental evidence previously published [1b] is supported by the findings described in this paper. We cannot agree that the isolation and characterization of a compound (I), which was postulated as a reactive kinetic intermediate, would present no difficulty. Thirdly, these authors state that "it should be emphasized that the tertiary amine initiated polymerizations usually proceed considerably faster than the corresponding primary or secondary amine initiated polymerizations. It can, therefore, hardly be visualized that both types of polymerization proceed by the same amine propagation mechanism." This entirely disregards the possibility fully discussed in the paper referred to [1b] that the tertiary base may act as a catalyst in a manner similar to that given above (equations 7 and 8). In our comprehensive scheme the concentration of (VII), which determines the rate of reaction in all cases, can build up to a much higher value under these conditions. This is true even if reactions (7) and (8) have rates of the same order as the association (1). The rate of the latter would be expected to be comparable for all amines of the same base strength which do not differ appreciably in the steric shielding of the nitrogen lone pair.

Kopple,[11] in considering the reactions of oxazolidine-2,5-diones, doubted whether the ring system is sufficiently acidic to allow the formation of the ion (VI); this doubt could obviously be applied to the formation of an ion (V) from 3-methylhydantoin and

[10] Wieland, *Angew. Chem.*, 1951, **63**, 7; 1954, **66**, 507.
[11] Kopple, *J. Amer. Chem. Soc.*, 1957, **79**, 6442.

can now hardly be maintained. Moreover, this author himself postulates the formation of anions of type (VI). We consider that both ions (V) and (VI) are formed to kinetically significant extents as transient intermediates, a hypothesis which is consistent with the heterocyclic ring systems' being extremely weak acids.

We do not consider a reaction scheme such as that proposed by Kopple, involving isocyanate intermediates in polymerization by a tertiary base, to be applicable, since if initiation by a primary base followed this presumably faster route urea derivatives would be expected, together with low yields of carbon dioxide and loss of primary end groups.

We thank Mr. D. R. Boreham, Mrs, S. J. Kapur, and Mrs. Z. Watson for technical assistance.

COURTAULDS, LIMITED, RESEARCH LABORATORY,
MAIDENHEAD, BERKS. [*Received, October 21st,* 1960.]

---

392. *Steric Effects on the Spectra of Aromatic Hydrocarbons.*

By R. I. T. CROMARTIE and J. N. MURRELL.

It is shown how the sign of a sterically induced frequency shift of the *p*-band of an alternant hydrocarbon can be predicted theoretically. The predictions are in agreement with experimental findings for the cases examined.

STERIC distortion of an aromatic hydrocarbon can give rise to either a hyposchromic or a bathochromic shift in the absorption bands. In this paper we show how the sign of this shift can be predicted in a simple way for the so-called *p*-band (Clar) (Platt's L_b band). In all cases which we have examined, where the method of relieving the steric strain has been established or can be inferred from the examination of molecular models, our predictions agree with the experimental results.

The *p*-band arises from the excitation of an electron from the highest occupied molecular orbital of the ground state to the lowest unoccupied orbital. It occurs with moderate intensity as either the first or the second band in the spectrum. It has been shown that the energy of this band in a series of aromatic hydrocarbons is well correlated with the difference in energy between the highest occupied and lowest unoccupied orbital, as calculated by the Hückel L.C.A.O. theory with zero-overlap approximation.[1] In this theory the orbitals of the so-called alternant hydrocarbons (those with no odd-membered rings) occur in pairs with energies $\alpha \pm E_r$, the energy E_r being given by $\sum_{\mu}^{*}\sum_{\nu}^{\circ} C_{r\mu}C_{r\nu}\beta_{\mu\nu}$. $C_{r\mu}$ is the coefficient of the μth atomic orbital in the rth molecular orbital, and $\beta_{\mu\nu}$, the resonance integral between orbitals μ and ν, which is taken to be zero unless atoms μ and ν are bonded together. The summation $\sum^{*}$ is over starred atoms and $\sum^{\circ}$ over unstarred, so that no two atoms of the same set are bonded together.

Now $\beta_{\mu\nu}$ is a negative quantity; hence if $C_{r\mu}$ and $C_{r\nu}$ are both positive, the term $C_{r\mu}C_{r\nu}\beta_{\mu\nu}$ contributes negatively to E_r, that is stabilises orbital ψ_r. Reducing the value of β in this case, by straining the molecule in some way, will therefore destabilise this orbital. However, if the coefficients $C_{r\mu}$ and $C_{r\nu}$ have opposite signs, then reducing the value of β will stabilise orbital ψ_r. The pair of orbitals which have energies $\alpha \pm E_r$ also have related coefficients, so that if the occupied orbital is written

$$\psi_r = \sum_{\mu}^{*} C_{r\mu}\phi_\mu + \sum_{\nu}^{\circ} C_{r\nu}\phi_\nu$$

then the corresponding unoccupied orbital is

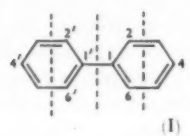
$$\psi_{-r} = \sum^{*} C_{r\mu}\phi_\mu - \sum_{\nu}^{\circ} C_{r\nu}\phi_\nu$$

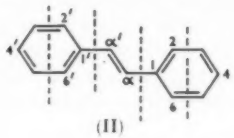
This means that if the bonding orbital ψ_r is lowered in energy, the corresponding antibonding

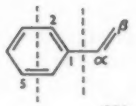
[1] Dewar, *J.*, 1952, 3532.

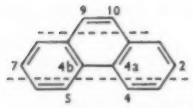
XUM

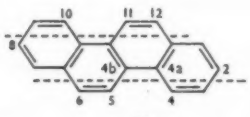
orbital ψ_r is raised in energy. The result is a hypsochromic shift in the absorption band associated with the excitation $\psi_r \longrightarrow \psi_{-r}$. From this result we predict: (*a*) if the highest occupied orbital has a node through the bond across which the steric strain is being

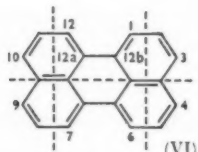

(I)

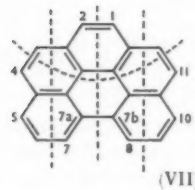

(II)

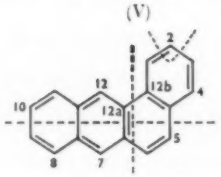

(III)

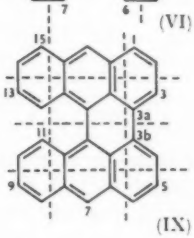

(IV)

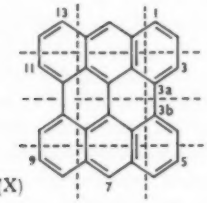

(V)

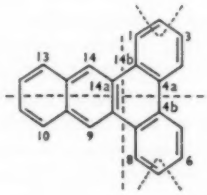

(VI)


(VII)


(VIII)


(IX)


(X)


(XI)

Aromatic system	Substituent	Bonds principally twisted	Predicted frequency shift	Exptl. ($cm.^{-1}$)
Biphenyl (I)	2,4,6,2′,4′,6′-hexamethyl	1,1′	+	+5000 [g]
trans-Stilbene (II)	2,4,6,2′,4′,6′-hexamethyl	α,1 and α′,1′	+	+4100 [a]
Styrene (III)	α-methyl	α,1	+	+800 [b]
Phenanthrene (IV)	4,5-dimethyl	4a,4b	—	−2300 [g]
Chrysene (V)	4,5-dimethyl	4a,4b	—	−2300 [g]
Perylene (VI)	1,12-diacetoxy	12a,12b	+	+610
Benzo[*ghi*]perylene (VII)	7,8-di(hydroxymethyl)	7a,7b	+	+1110 [e]
Benz[*a*]anthracene (VIII) (tetraphene)	1,12-dimethyl	12a,12b	+	0 [d]
Dibenzo[*a*,*o*]perylene (IX) (helianthrene)	3,4-dimethyl	3a,3b	+	+850 [c] †
Phenanthro[1,10,9,8-*opqra*]perylene (*meso*-Naphthodianthrene) (X)	3,4-dimethyl	3a,3b	+	+800 [f] ‡
Dibenz[*a*,*c*]anthracene (XI)	4,5-dimethyl 1,14-dimethyl	4a,4b 14a,14b	+ +	

† The orbitals for this molecule were calculated for us by Dr. T. Farrar on the EDSAC computer at the Mathematical Laboratory, Cambridge.

‡ The form of the highest orbital was obtained from the orbitals of helianthrene by perturbation theory.

[a] Beale and Roe, *J. Amer. Chem. Soc.*, 1952, **74**, 2302. [b] Gillam and Stern, "Electronic Absorption Spectroscopy," Arnold, London, 1958. [c] Baykut and Cromartie, unpublished work. [d] Cason and Phillips, *J. Org. Chem.*, 1952, **17**, 298. [e] Brockmann, von Falkenhausen, Neeff, Dorlars, and Budde, *Chem. Ber.*, 1951, **84**, 865. [f] Brockmann and Randebrock, *Chem. Ber.*, 1951, **84**, 533. [g] Friedel and Orchin, ref. 3.

XUM

relieved, the *p*-band (L_b) will be hypsochromically shifted by the steric effect; (*b*) if there is no node the band will be bathochromically shifted.†

The Table gives the predicted and observed direction of the steric effect for a number of condensed aromatic hydrocarbons, as deduced from the form of the highest occupied molecular orbital. Broken lines indicate the nodes in these orbitals, which have been taken from the published tables [2] except where indicated. In some cases the geometry of the strained molecule has not been determined by *X*-ray analysis; but the probable mode of distortion has been inferred from the examination of Dreiding molecular models, and also from the fact that twisting a bond of low bond-order leads to less destabilization of the π-electron system than twisting one with a high bond-order. Thus in stilbene and styrene it is assumed that the twisting takes place mainly about the single bonds of the classical structure.

The *p*-band of 4,5-dimethylphenanthrene shows a considerably greater bathochromic shift ($\Delta\nu = -2300$ cm.$^{-1}$) than those of the other isomers, *e.g.*, for 2,5-dimethylphenanthrene $\Delta\nu = -570$ cm.$^{-1}$.[3] The overcrowding in molecules of this type is known from Newman's work to be relieved by displacement of the substituents out of plane of the aromatic system with concomitant distortion of the latter.[4] Examination of models shows that the 4a,4b-bond would be the most twisted, and this bond also has a low bond-order. Similar considerations apply to the case of 4,5-dimethylchrysene.

No 1,12-dialkylperylene has yet been made, but 1,12-diacetoxyperylene, which was prepared by the method of Zinke, Penecke, and Hanus,[5] showed a hypsochromic shift; this agrees with the theory if the strain is relieved by twisting the two central bonds joining the two naphthalene units. These bonds have low bond-order and are known to be of mostly single-bond length from the *X*-ray analysis of perylene.[6] A similar type of distortion is assumed for derivatives of benzo[*ghi*]perylene, *meso*-naphthodianthrene and helianthrene bearing substituents in corresponding positions, and hypsochromic shifts are observed in all these cases.

The benz[*a*]anthracene system is a more subtle case. This molecule can be compared with phenanthrene but unlike it the highest occupied molecular orbital has a node across the 12a,12b bond. The product of the coefficient across this bond is, however, rather small (0·0016) and it is therefore predicted that if the resonance integral across this bond were decreased a small hypsochromic shift would be observed. Experimentally it is observed that substitution of a single 12-methyl group brings about a bathochromic shift ($\Delta\nu = 920$ cm.$^{-1}$) but that the 1-methyl derivative and the sterically hindered 1,12-dimethyl derivative absorb at very nearly the same frequency as the unsubstituted hydrocarbon.[7] It is therefore concluded that the hypsochromic shift due to steric distortion cancels out the normal bathochromic effect of methylation. Another interesting case would be dibenz[*a*,*c*]anthracene in which a hypsochromic shift would be predicted for substitution in the 4,5- or 1,14-positions; but no compounds of this type are known.

The authors are grateful to Mr. P. M. Scott for the preparation of 1,12-diacetoxyperylene.

UNIVERSITY CHEMICAL LABORATORY, CAMBRIDGE. [*Received, November* 14*th*, 1960.]

† This approach is similar to that used by Heilbronner and Gerdil (*Helv. Chim. Acta*, 1956, **39**, 1996) and by Dewar ("Steric Effects in Conjugated Systems," ed. Gray, Butterworths, London, 1958, p. 46).

[2] Coulson and Daudel, "Dictionary of Molecular Constants," Centre National de la Recherche Scientifique, Paris.

[3] Friedel and Orchin, "Ultra-violet Spectra of Aromatic Compounds," John Wiley and Sons Inc., New York, 1951.

[4] Newman, *J. Amer. Chem. Soc.*, 1940, **62**, 2295; Newman and Hussey, *ibid.*, 1947, **69**, 3023; Newman and Whitehouse, *ibid.*, 1949, **71**, 3664.

[5] Zinke, Penecke, and Hanus, *Ber.*, 1936, **69**, 624.

[6] Robertson and White, *Proc. Roy. Soc.*, 1953, *A*, **220**, 311.

[7] Jones, *J. Amer. Chem. Soc.*, 1940, **62**, 148; Cason and Phillips, *J. Org. Chem.*, 1952, **17**, 298.

XUM

393. *Sulphur Chloride Pentafluoride: Reaction with Unsaturated Hydrocarbons.*

By J. R. Case, N. H. Ray, and H. L. Roberts.

Sulphur chloride pentafluoride adds to certain olefins and chloro-olefins to give 2-chloroalkylsulphur pentafluorides; acetylene and propyne give 2-chlorovinyl- and 2-chloropropenyl-sulphur pentafluoride, respectively. These products eliminate hydrogen chloride on treatment with potassium hydroxide, to give pentafluorosulphur-substituted olefins and acetylenes.

Sulphur chloride pentafluoride[1] does not react with paraffin hydrocarbons, but when heated under moderate pressures with certain olefins and chloro-olefins it adds to the double bond, giving 2-chloroalkylsulphur pentafluorides:

$$SF_5Cl + R{\cdot}CH{:}CH_2 \longrightarrow R{\cdot}CHCl{\cdot}CH_2{\cdot}SF_5$$

This reaction has been carried out with ethylene, propene, cyclohexene, butadiene, and vinyl chloride; it failed with isobutene and styrene because these olefins polymerised very rapidly in the presence of sulphur chloride pentafluoride. Ethylene and vinyl chloride also showed a tendency to polymerise, for the simple addition compounds were accompanied by smaller amounts of higher-boiling fractions from which compounds were isolated which were evidently telomers containing two molecules of the olefin. The 2-chloroalkylsulphur pentafluorides eliminated hydrogen chloride on treatment with potassium hydroxide, to give the corresponding unsaturated pentafluorosulphur compounds; however, it was not possible to remove more than one molecule of hydrogen chloride from 2,2-dichloroethylsulphur pentafluoride, and attempts to prepare the substituted acetylene from this compound only resulted in complete decomposition.

Addition of sulphur chloride pentafluoride to propene gave a high yield of 2-chloropropylsulphur pentafluoride, the structure of which was established by showing that two isomeric pentafluorosulphur-substituted propenes were formed by elimination of hydrogen chloride whereas 2-chloro-1-methylethylsulphur pentafluoride could only give one compound:

$$CH_3{\cdot}CHCl{\cdot}CH_2{\cdot}SF_5 \longrightarrow CH_2{:}CH{\cdot}CH_2{\cdot}SF_5 + CH_3{\cdot}CH{:}CH{\cdot}SF_5$$

$$CH_3{\cdot}CH(SF_5){\cdot}CH_2Cl \longrightarrow CH_2{\cdot}C(SF_5){:}CH_2$$

The isomers were separated by gas chromatography and differentiated by their infrared absorption spectra; a more detailed account of the spectra of compounds containing the pentafluorosulphur group is to be published elsewhere.

Even with an excess of sulphur chloride pentafluoride only one molecular proportion reacted with butadiene, and some polymer was also produced. The main product is believed to be 2-chlorobut-3-enylsulphur pentafluoride rather than the isomeric 4-chlorobut-2-enyl derivative because its infrared absorption spectrum showed bands which are attributed to a vinyl group.

With cyclohexene, in addition to the expected 2-chlorocyclohexylsulphur pentafluoride, a chlorofluorocyclohexane was formed as a by-product. This is assumed to be 1-chloro-2-fluorocyclohexane, and a possible mechanism for its formation is discussed below.

Vinyl chloride with sulphur chloride pentafluoride gave 2,2-dichloroethylsulphur pentafluoride and not the 1,2-dichloro-analogue, for the latter isomer was obtained by chlorination of vinylsulphur pentafluoride and was shown to be a different compound:

$$CH_2{:}CHCl + SF_5Cl \longrightarrow SF_5{\cdot}CH_2{\cdot}CHCl_2$$

$$CH_2{:}CH{\cdot}SF_5 + Cl_2 \longrightarrow CH_2Cl{\cdot}CHCl{\cdot}SF_5$$

[1] Roberts and Ray, *J.*, 1960, 665.

XUM

Sulphur chloride pentafluoride also adds to the triple bond in acetylene and propyne; the product from propyne was shown to be 2-chloropropenylsulphur pentafluoride by reaction with potassium hydroxide which gave prop-1-ynylsulphur pentafluoride; the isomeric 2-chloro-1-methylethyl compound could not give this reaction:

$$CH_3{\cdot}C{\vdots}CH + SF_5Cl \longrightarrow CH_3{\cdot}CCl{:}CH{\cdot}SF_5 \longrightarrow CH_3{\cdot}C{\vdots}C{\cdot}SF_5$$

Some of the reactions described above were also carried out at atmospheric pressure with ultraviolet irradiation; the products thus obtained from propene and from propyne were identical with the corresponding products from autoclave reactions. For safety reasons the addition of sulphur chloride pentafluoride to acetylene was attempted only at atmospheric pressure, under the influence of ultraviolet light.

The products obtained in these reactions are generally those to be expected if sulphur chloride pentafluoride adds to olefins by a free-radical mechanism; and the isolation of telomers from the reactions with ethylene and vinyl chloride supports this view. The initial attack of a radical on sulphur chloride pentafluoride is more likely to be at the chlorine than at the sulphur atom, owing to the screening effect of the fluorine atoms; the orientation of the products obtained from propene, vinyl chloride, and propyne can be explained on this basis:

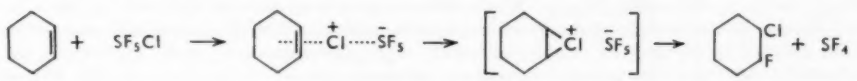
$$R{\cdot} + SF_5Cl \longrightarrow RCl + SF_5$$

$$SF_5{\cdot} + CH_2{\cdot}CH{:}CH_2 \longrightarrow CH_2{\cdot}\dot{C}H{\cdot}CH_2{\cdot}SF_5$$

$$CH_2{\cdot}\dot{C}H{\cdot}CH_2{\cdot}SF_5 + SF_5Cl \longrightarrow CH_2{\cdot}CHCl{\cdot}CH_2{\cdot}SF_5 + SF_5{\cdot}$$

Further examples of radical reactions involving sulphur chloride pentafluoride will be described in a subsequent publication.

The rapid polymerisation of isobutene and styrene by sulphur chloride pentafluoride suggests that it can sometimes react ionically, and the formation of chlorofluorocyclohexane from cyclohexene is probably the result of attack by a sulphur chloride pentafluoride molecule on the olefin, followed by heterolysis of the S–Cl bond; the labile species SF_5^- would quickly decompose into a fluoride ion and the stable molecule SF_4:



Experimental

Apparatus and Procedure.—Autoclave reactions were normally carried out in a stainless-steel autoclave of 250 c.c. capacity and 2500 atm. maximum working pressure, fitted with a bursting disc (usually 1000 atm.) close to the head of the vessel, and provided with a magnetically operated reciprocating stirrer. For some experiments a similar autoclave of 100 c.c. capacity and 3000 atm. maximum working pressure was used. The autoclave was heated by a copper-block electric furnace and the temperatures measured were the temperatures of the outer wall of the vessel, adjacent to the furnace.

The autoclave was charged with sulphur chloride pentafluoride by evacuating it, cooling it with liquid air, and distilling in the required amount of reagent from a weighed cylinder. Other gaseous reagents were added in a similar way; liquid reagents were put into the autoclave before it was evacuated. After the reaction the autoclave was cooled to room temperature and any gas pressure remaining was released through a system of traps cooled in liquid air. The traps were allowed to warm slowly to room temperature and their residual contents were combined with the contents of the autoclave.

Reaction of Sulphur Chloride Pentafluoride with Unsaturated Hydrocarbons.—Ethylene. Sulphur chloride pentafluoride (approx. 1 mole) and ethylene (approx. 1 mole) were heated together at 90° for 10 hr. The pressure was initially 250 atm., falling to 30 atm. at the end of the reaction. The products from four experiments, involving a total of 686 g. (4·22 moles) of sulphur chloride pentafluoride, were combined for working up. The liquid (515 g.) was washed

with sodium hydrogen carbonate solution, dried ($CaCl_2$), and distilled, giving *2-chloroethylsulphur pentafluoride* (377 g., 47%), b. p. 92°, n_D^{20} 1·3590, d_4^{20} 1·64 (Found: C, 12·7; H, 2·3; Cl, 19·1; F, 52·0; S, 16·1%; *M*, 190. $C_2H_4ClF_5S$ requires C, 12·6; H, 2·1; Cl, 18·6; F, 49·9; S, 16·8%; *M*, 190·5). Its infrared absorption spectrum showed an intense band centred on 870 cm.$^{-1}$ which is characteristic of the SF_5 group.

The higher-boiling residue yielded a fraction (78 g.), b. p. 171—172°, which is believed to be *4-chlorobutylsulphur pentafluoride* (Found: C, 23·0; H, 3·3; Cl, 16·2; F, 43·5; S, 15·3%; *M*, 212. $C_4H_8ClF_5S$ requires C, 22·0; H, 3·6; Cl, 16·2; F, 43·5; S, 14·6%; *M*, 218·5). Its infrared absorption spectrum showed an intense band at 870 cm.$^{-1}$.

Propene. Sulphur chloride pentafluoride (165 g., 1·01 mole) and propene (42 g., 1·0 mole) were heated for 3 hr. at 100°. The pressure was initially 40 atm. and fell to about 2 atm. at the end of the reaction. The product (184 g.) was washed with sodium hydrogen carbonate solution, dried ($CaCl_2$), and distilled, giving *2-chloropropylsulphur pentafluoride* (161 g., 78%), b. p. 109° (Found: C, 17·8; H, 3·2; Cl, 16·6; F, 41·3; S, 15·8%; *M*, 199. $C_3H_6ClF_5S$ requires C, 17·6; H, 3·0; Cl, 17·4; F, 46·5; S, 15·7%; *M*, 204·5). Its infrared absorption spectrum showed an intense band at 870 cm.$^{-1}$.

Butadiene. Sulphur chloride pentafluoride (158 g., 0·97 mole) and butadiene (20 g., 0·37 mole) were heated at 100° for 2 hr. The product (66 g.) was washed with sodium hydrogen carbonate solution and distilled with steam; the residue appeared to be a polymer of butadiene. The lower layer of the distillate was dried ($CaCl_2$) and distilled, giving a fraction (29·5 g.), b. p. 78—80°/26 mm., believed to be *2-chlorobut-3-enylsulphur pentafluoride* (Found: C, 22·2; H, 3·3; Cl, 20·2; F, 44·0; S, 14·3. $C_4H_6ClF_5S$ requires C, 22·0; H, 3·2; Cl, 16·2; F, 43·5; S, 14·6%). Its infrared absorption spectrum showed an intense band at 870 cm.$^{-1}$ (SF_5) and strong bands at 970 and 890 cm.$^{-1}$ (vinyl).

Isobutene. Sulphur chloride pentafluoride (160 g.) and isobutene (50 g.) were heated at 100° for 3 hr. There was no pressure change, and the product was found to be a mixture of carbon and polyisobutene; most of the sulphur chloride pentafluoride was recovered unchanged, accompanied by a minor amount of sulphur tetrafluoride.

Cyclohexene. Sulphur chloride pentafluoride (160 g.) and cyclohexene (77 g.) were stirred at 20° for 18 hr. The product (200 g.) was washed with aqueous sodium hydrogen carbonate and distilled with steam. The lower layer of the distillate was dried ($CaCl_2$) and fractionally distilled, giving cyclohexene (15 g.), b. p. 83°, and two main fractions: (i) b. p. 150—152° (25 g.), (ii) b. p. 188—190° (37 g.). The residue could not be distilled without decomposition.

Fraction (i) was a chlorofluorocyclohexane, presumably *1-chloro-2-fluorocyclohexane* (Found: C, 52·5; H, 7·3; Cl, 25·9; F, 13·9%; *M*, 141. $C_6H_{10}ClF$ requires C, 52·6; H, 7·3; Cl, 26·0; F, 15·6%; *M*, 137). Its infrared absorption spectrum showed strong bands at 740, 800, 955, 1460, and 2900 cm.$^{-1}$, with a triplet at 1044 cm.$^{-1}$.

Fraction (ii) was *2-chlorocyclohexylsulphur pentafluoride*, n_D^{20} 1·4320, d_D^{20} 1·4783 (Found: C, 29·8; H, 4·3; Cl, 14·6; F, 36·9; S, 12·6%; *M*, 245. $C_6H_{10}ClF_5S$ requires C, 29·4; H, 4·1; Cl, 14·5; F, 38·8; S, 13·1%; *M*, 244·5), having $\nu_{max.}$ 870 cm.$^{-1}$.

Styrene. Styrene (10 ml.) was stirred at atmospheric temperature and pressure in a flask from which the air had been displaced by sulphur chloride pentafluoride. After about 30 min., there was a violent exothermic reaction and the product was mainly polystyrene. Its infrared absorption spectrum showed no bands that were not also present in the spectrum of normal polystyrene.

Propyne. Sulphur chloride pentafluoride (90 g.) and propyne (20 g.) were heated at 90° for 4 hr. in a 100 c.c. autoclave. The product (47 g.) was washed with dilute potassium carbonate solution and dried ($MgSO_4$). Distillation gave as a main fraction *2-chloropropenylsulphur pentafluoride* (25 g.), b. p. 92° (Found: C, 17·2; H, 2·6; Cl, 18·4; F, 44·6; S, 16·6. $C_3H_4ClF_5S$ requires C, 17·7; H, 2·0; Cl, 17·6; F, 46·8; S, 15·8%), and an unidentified higher-boiling fraction (8 g.). The infrared absorption spectrum of the main fraction showed an intense band at 870 cm.$^{-1}$ (SF_5) and strong bands at 990, 1100, and 1650 cm.$^{-1}$, indicating unsaturation.

Vinyl chloride. Sulphur chloride pentafluoride (149 g.) and vinyl chloride (38 g.) were heated at 150° for 6 hr. in an autoclave. The product (116 g.) was washed with dilute potassium carbonate solution, dried, and distilled, giving (i) *2,2-dichloroethylsulphur pentafluoride* (50 g.), b. p. 108° (Found: C, 11·0; H, 1·4; Cl, 32·7; F, 40·6; S, 13·9%; *M*, 221. $C_2H_3Cl_2F_5S$ requires C, 10·7; H, 1·4; Cl, 31·6; F, 42·0; S, 14·2%; *M*, 225), and (ii) a fraction (22 g.), b. p. 72°/9 mm., believed to be *2,4,4-trichlorobutylsulphur pentafluoride* (Found: C, 16·6; H, 2·7; Cl, 38·1;

XUM

F, 30·9; S, 11·5%; *M*, 267. $C_4H_6Cl_3F_5S$ requires C, 16·7; H, 2·1; Cl, 37·1; F, 33·0; S, 11·1%; *M*, 288).

Preparation of Unsaturated Sulphur Pentafluoride Compounds.—Vinylsulphur pentafluoride. Potassium hydroxide (19 g.) was dissolved in water (20 c.c.), and ethanol (60 c.c.) added. This solution was boiled under a reflux condenser, the outlet of which was connected to a trap cooled with solid carbon dioxide and methanol. 2-Chloroethylsulphur pentafluoride (33 g.) was added to the solution from a tap-funnel during 15 min. Boiling was continued for 1 hr. after all the reagent had been added. The reflux condenser was then heated by passing water at 50° ± 5° through it, and the reaction flask was kept at 70° until no more liquid collected in the cold trap. The product was redistilled, giving *vinylsulphur pentafluoride* (22·5 g., 85%), b. p. 41° (Found: C, 15·9; H, 2·0; F, 61·3; S, 21·0%; *M*, 153. $C_2H_3F_5S$ requires C, 15·6; H, 2·0; F, 61·6; S, 20·9%; *M*, 154). The vapour pressure of this compound was measured and the results fitted the equation [v. p. (mm.) at T°K]: $\log_{10} p = -3420/T + 13{\cdot}68$. The latent heat of vaporisation is 6800 cal. per mole, and the Trouton constant is 21·6. The infrared absorption spectrum of the liquid showed an intense band at 870 cm.$^{-1}$ (SF_5) and strong bands at 965, 1040, and 1390 cm.$^{-1}$.

Allylsulphur pentafluoride and propenylsulphur pentafluoride. A mixture of potassium hydroxide (75 g.), methanol (300 c.c.), and 2-chloropropylsulphur pentafluoride (145 g.) was heated under reflux for 2½ hr., then allowed to cool and stored at room temperature for 12 hr. The mixture was added to 1 l. of water, and the lower layer was separated, washed with water, and dried ($MgSO_4$). A Beilstein test showed that chlorine was absent. The liquid was fractionally distilled, giving a main fraction (43 g.), b. p. 80—82°, and a higher-boiling residue which was not examined. The main fraction was separated by gas chromatography into two components: that of shorter retention time (4·4 g.) was *allylsulphur pentafluoride* (Found: C, 21·7; H, 3·0; F, 54·3; S, 19·0%; *M*, 168. $C_3H_5F_5S$ requires C, 21·4; H, 3·0; F, 56·5; S, 19·0%; *M*, 168). The second and larger fraction (38·5 g.) was *propenylsulphur pentafluoride* (Found: C, 22·0; H, 2·7; F, 54·3; S, 19·1%; *M*, 170). The infrared absorption spectra of both of these compounds showed bands at 602, 606, 613, and 885 cm.$^{-1}$; propenylsulphur pentafluoride also showed methyl bands at 1449, 2865, and 2967 cm.$^{-1}$, and allylsulphur pentafluoride showed vinyl bands at 995 and 3090 cm.$^{-1}$.

Cyclohexenylsulphur pentafluoride. A mixture of 1-chlorocyclohexylsulphur pentafluoride (12·2 g.), potassium hydroxide (5·6 g.), water (5 c.c.), and ethanol (75 c.c.) in a 250 c.c. flask with a reflux condenser was cautiously warmed to about 75°; as soon as the reaction started, the heat was removed. After the initial exothermic reaction had subsided the mixture was boiled for 15 min., then cooled and poured into water (350 c.c.). The lower layer was separated, dried ($MgSO_4$), and distilled. *Cyclohexenylsulphur pentafluoride* (8 g., 79%) was collected at 112—115°/100 mm.; it had b. p. 161°/760 mm., n_D^{20} 1·4282 (Found: C, 34·9; H, 4·7; F, 44·2; S, 15·3%; *M*, 190. $C_6H_9F_5S$ requires C, 34·6; H, 4·3; F, 45·6; S, 15·4%; *M*, 208), $\nu_{max.}$ 870 (SF_5) and 940 cm.$^{-1}$ (unsaturation).

Prop-1-ynylsulphur pentafluoride. Powdered potassium hydroxide (10 g.) was suspended in ligroin (25 c.c.; b. p. 100—120°) and heated to 60° under a condenser. 2-Chloropropenylsulphur pentafluoride (10 g.) was added to the suspension and the mixture was kept at 75° for 20 min.; after cooling, it was filtered, and the filtrate distilled. The fraction of b. p. 65—70° (2 g.) was collected and divided by gas chromatography into two fractions: the retention time of the second was identical with that of the starting material; the sub-fraction of shorter retention time (*ca.* 0·2 g.) was *prop-1-ynylsulphur pentafluoride* (Found: F, 57·3; S, 18·7%; *M*, 166·5. $C_3H_3F_5S$ requires F, 57·5; S, 19·3%; *M*, 166). Its infrared absorption spectrum showed a band at 2261 cm.$^{-1}$ characteristic of C≡C, but no absorption at 3300 cm.$^{-1}$, indicating the absence of C–H. The S–F stretching frequencies were at 893 (vs), 855—852 (vs), 706—704—697 cm.$^{-1}$ and the S–F deformation was at 622—618—612 cm.$^{-1}$. The P–R separation is that expected for a symmetric top molecule whose moments of inertia correspond to $SF_5{\cdot}C{\equiv}C{\cdot}CH_3$.

2-Chlorovinylsulphur pentafluoride. 2,2-Dichloroethylsulphur pentafluoride (23 g.) was dissolved in methanol (25 c.c.) and cooled to −20°. A solution of potassium hydroxide (9 g.) in methanol (30 c.c.) was added dropwise, the temperature being kept between −20° and −10°. The mixture was filtered, and water (50 c.c.) added to the filtrate. The lower layer was separated, washed with saturated aqueous sodium chloride, dried ($MgSO_4$), and distilled, giving *2-chlorovinylsulphur pentafluoride* (12 g., 63%), b. p. 66° (Found: C, 11·9; H, 1·2;

XUM

Cl, 19·5; F, 49·8; S, 17·5%; *M*, 185. $C_3H_3ClF_8S$ requires C, 12·7; H, 1·1; Cl, 18·8; F, 50·4; S, 17·0%; *M*, 189), $\nu_{max.}$ 870 (SF_5) and 920 and 1580 cm.$^{-1}$ (unsaturation).

Photochemical Reactions of Sulphur Chloride Pentafluoride.—Apparatus and procedure. A Pyrex tube of 600 c.c. capacity was provided with an inner tube made of fused quartz containing a Hanovia 509/12 mercury discharge tube. The tube was vertical and liquid products were collected in a small well at the bottom. Gaseous reagents were introduced from a vacuum-line connected at the top of the reaction tube, and a mercury manometer was used to measure the pressure in the apparatus. In each experiment, equal volumes of the hydrocarbon and sulphur chloride pentafluoride were admitted to the previously evacuated reaction vessel, so that the pressure was approximately 1 atm. The discharge tube was energised, and irradiation of the mixture was continued until no further pressure change was observed. The liquid product was collected, and purified by gas chromatography.

Reaction with propene. The liquid product (3 c.c.) was chromatographically homogeneous and identical in chromatographic retention time and infrared absorption spectrum with the 2-chloropropylsulphur pentafluoride obtained in an autoclave.

Reaction with acetylene. The liquid product (2·5 c.c.) was almost pure 2-chlorovinylsulphur pentafluoride, identical in chromatographic retention time and infrared absorption spectrum with the product obtained by reaction of 2,2-dichloroethylsulphur pentafluoride with alkali.

Reaction with propyne. The product (3 c.c.) was identical with the sample of 2-chloropropenylsulphur pentafluoride obtained in an autoclave.

Chlorination of Vinyl Sulphur Pentafluoride.—A 10-l. photochemical reaction vessel was charged with chlorine to 0·5 atm. and the ultraviolet lamp was switched on. Vinylsulphur pentafluoride (39 g., 1·0 mol.) was added gradually from a tap-funnel; the pressure fell during 15 min. to about 10 cm. The product was a liquid containing some dissolved hydrogen chloride, but free from chlorine. It was washed with dilute potassium carbonate solution and water, dried ($MgSO_4$), and distilled, giving (i) recovered vinylsulphur pentafluoride (6·8 g.), b. p. 41—42°, (ii) 1,2-dichloroethylsulphur pentafluoride (18·5 g.), b. p. 111°, and (iii) a higher-boiling residue which was not examined. The infrared absorption spectra of fraction (ii) from this experiment and of 2,2-dichloroethylsulphur pentafluoride prepared from vinyl chloride and sulphur chloride pentafluoride (see above) were compared, and the following observations were made: both compounds showed very strong absorption bands in the region of 860 cm.$^{-1}$ (SF_5) and moderately strong bands in the region from 1300 to 1450 cm.$^{-1}$ due to C–H bonds; there were marked differences in the region from 700 to 800 cm.$^{-1}$, where 2,2-dichloroethylsulphur pentafluoride showed a single strong absorption at 772 cm.$^{-1}$, and 1,2-dichloroethylsulphur pentafluoride [fraction (ii) from this experiment] showed a pair of strong bands at 781 and 732 cm.$^{-1}$. Their retention times on a gas-chromatography column were in the ratio of 1 to 1·12.

IMPERIAL CHEMICAL INDUSTRIES LIMITED,
ALKALI DIVISION RESEARCH DEPARTMENT,
WINNINGTON, NORTHWICH, CHESHIRE.

[*Received, September 28th*, 1960.]

---

394. *Sulphur Chloride Pentafluoride: Reaction with Fluoro-olefins.*

By J. R. CASE, N. H. RAY, and H. L. ROBERTS.

Sulphur chloride pentafluoride adds to tetrafluoroethylene, trifluoroethylene, chlorotrifluoroethylene, and hexafluoropropene, to give 2-chloropolyfluoroalkylsulphur pentafluorides. The orientation of the products formed has been determined, and a possible mechanism for the reactions is suggested.

THE reaction of sulphur chloride pentafluoride with hydrocarbon olefins was described in the preceding paper.[1] The reaction can take place either in the gas phase under the influence of ultraviolet light or in the liquid phase at an appropriate temperature, which

[1] Case, Ray, and Roberts, preceding paper.

depends on the olefin used. With fluorocarbon olefins the reactions did not take place as readily; a free-radical initiator was desirable in the liquid-phase reactions to obtain reproducible results, and the gas-phase reactions gave other products in addition to chlorofluoroalkylsulphur pentafluorides.

With tetrafluoroethylene, sulphur chloride pentafluoride when in excess and in the presence of dibenzoyl peroxide as a catalyst at 100° reacts smoothly to give mainly 2-chlorotetrafluoroethylsulphur pentafluoride:

$$SF_5Cl + C_2F_4 \longrightarrow SF_5{\cdot}CF_2{\cdot}CF_2Cl$$

If, however, the tetrafluoroethylene is in excess, telomers of the type $SF_5{\cdot}[CF_2{\cdot}CF_2]_n{\cdot}Cl$ are obtained, the mean molecular weight, judged from the amount of high-boiling material present, depending on the molar ratio of sulphur chloride pentafluoride to tetrafluoroethylene.

Under similar conditions trifluoroethylene also reacts with sulphur chloride pentafluoride to give mainly 1 : 1 addition:

$$SF_5Cl + CHF{=}CF_2 \longrightarrow SF_5{\cdot}CHF{\cdot}CF_2Cl$$

This compound, unlike all the other compounds prepared in which SF_5 is attached to carbon, is unstable to aqueous alkali and decomposes, giving sulphite ions. The orientation of the addition reaction is proved by the reaction of the product with powdered potassium hydroxide in light petroleum, which gives perfluorovinylsulphur pentafluoride:

$$SF_5{\cdot}CHF{\cdot}CF_2Cl \xrightarrow{KOH} SF_5{\cdot}CF{=}CF_2 + HCl$$

Chlorotrifluoroethylene also reacts with sulphur chloride pentafluoride under these conditions to give some 2,2-dichlorotrifluoroethylsulphur pentafluoride and much higher-boiling material, presumably telomers:

$$SF_5Cl + CF_2{=}CFCl \longrightarrow SF_5{\cdot}CF_2{\cdot}CFCl_2$$

This compound has been shown by its infrared spectrum to be an isomer of the compound obtained by chlorination of vinylsulphur pentafluoride whose structure can only be $SF_5{\cdot}CFCl{\cdot}CF_2Cl$.

In contrast to the three olefins so far discussed, hexafluoropropene does not react with sulphur chloride pentafluoride in the presence of benzoyl peroxide at 150°.

Under the influence of ultraviolet light tetrafluoroethylene, chlorotrifluoroethylene, and hexafluoropropene all react with sulphur chloride pentafluoride. In contrast to the behaviour of hydrocarbon olefins, which gave exclusively 1 : 1 addition under these conditions, a complex mixture was obtained. With tetrafluoroethylene, in addition to all the products observed in the free-radical catalysed reaction, 1,2-dichlorotetrafluoroethane $ClCF_2{\cdot}CF_2Cl$ and disulphur decafluoride were obtained among the lower-boiling fractions, and it is probable that the higher-boiling fractions contained telomers of the type $Cl{\cdot}[C_2F_4]_n{\cdot}Cl$. Hexafluoropropene gave a similar result, although the known reluctance of this olefin to polymerise meant that only compounds of low molecular weight were obtained. The result obtained with chlorotrifluoroethylene was of great interest, for in addition to the expected disulphur decafluoride and 1,2,2-trichlorotrifluoroethane, a compound was obtained in which one molecule of sulphur chloride pentafluoride had added to one molecule of olefin; this is the isomer of that obtained in the free-radical catalysed reaction:

$$SF_5Cl + CF_2{=}CFCl \longrightarrow SF_5{\cdot}CFCl{\cdot}CF_2Cl$$

This compound has an infrared spectrum identical with that obtained from the reaction of chlorine with perfluorovinylsulphur pentafluoride. As with tetrafluoroethylene, in addition to the simple compounds mentioned, much higher-boiling material was obtained.

XUM

Experimental

Apparatus and Procedure.—Autoclave reactions were carried out in a stainless-steel autoclave of 100 c.c. capacity or a " Hastelloy C " autoclave of 55 c.c. capacity, both vessels being fitted with an electromagnetically operated reciprocating stirrer and having a maximum safe working pressure of 3000 atm. The experimental technique employed has been described in the preceding paper.

The columns used for gas-chromatographic analysis were packed with " Chromosorb " on which dinonyl phthalate, silicone grease, or a chlorofluorocarbon grease had been deposited. All these columns were tried before a given peak was assumed to contain only one substance.

Reaction of Sulphur Chloride Pentafluoride with Unsaturated Fluorocarbons.—Tetrafluoroethylene. Sulphur chloride pentafluoride (61 g.), tetrafluoroethylene (22 g.), and dibenzoyl peroxide (0·8 g.) were heated at 90° for 10 hr. The liquid product (49 g.) was washed with N-potassium hydroxide, water, and saturated brine and dried ($MgSO_4$). It gave the following fractions on distillation: (1) b. p. 44—54° (18·3 g.), (2) b. p. 90—102° (8·6 g.), and a residue of 4·2 g. Fraction (1) was carefully redistilled and gave *2-chlorotetrafluoroethylsulphur pentafluoride* (14 g.), m. p. −113°, b. p. 47° (Found: C, 9·6; Cl, 14·0; F, 65·8; S, 12·5%; *M*, 261. C_2ClF_9S requires C, 9·2; Cl, 13·5; F, 65·2; S, 12·2%; *M*, 262·5). The vapour pressure of this compound was measured and fits the equation $\log_{10} p = -1479/T + 7{\cdot}494$. The b. p. found by extrapolation was 47·5°, the latent heat of vaporisation calculated from the slope is 6770 cal. mole^{-1}, and the Trouton constant is 21·1. The infrared absorption spectrum showed intense bands at 1215, 1190, 1135, 1070, 1050, 950, 900vs, 840, 795vs cm.$^{-1}$.

Sulphur chloride pentafluoride (24 g.), tetrafluoroethylene (18 g.), and dibenzoyl peroxide (0·4 g.), dissolved in trichlorofluoromethane (30 g.), were heated at 100° for 10 hr. The liquid product (73 g.) was distilled. The first fraction, b. p. up to 30° (63·4 g.), was shown by gas chromatography to consist of three components whose retention times were equal to those of sulphur chloride pentafluoride, trichlorofluoromethane, and the preceding product respectively. There was then a sharp rise in b. p. to 90° at which a fraction (5 g.) of b. p. 90—110° was obtained. The residue (6 g.) solidified at room temperature. In a similar experiment sulphur chloride pentafluoride (21 g.) and tetrafluoroethylene (30 g.) gave products (18·3 g.) which were solid at room temperature, in addition to the usual liquid products.

The fractions boiling above 90° from several experiments were collected and fractionated, giving *4-chloro-octafluorobutylsulphur pentafluoride*, m. p. −90°, b. p. 99° (Found: C, 13·0; Cl, 10·2; F, 68·4; S, 9·0%; *M*, 357. $C_4ClF_{13}S$ requires C, 13·3; Cl, 9·8; F, 68·2; S, 8·8%; *M*, 362·5) and *6-chlorododecafluorohexylsulphur pentafluoride*, m. p. −5°, b. p. 142° (Found: C, 15·6; Cl, 8·5; F, 68·0; S, 7·5%; *M*, 467. $C_6ClF_{17}S$ requires C, 15·6; Cl, 7·7; F, 69·4; S, 6·9%; *M*, 462·5).

Higher telomers $SF_5{\cdot}[CF_2{\cdot}CF_2]_n{\cdot}Cl$ were no doubt present in the higher-boiling fractions but were not isolated as pure compounds. Gas-chromatographic analysis of the products showed no trace of compounds boiling below 142° other than those mentioned. In the portion boiling above 142° one fraction obtained by gas chromatography was identified by its retention time and infrared spectrum as chlorobenzene.

Trifluoroethylene. Sulphur chloride pentafluoride (46 g.), trifluoroethylene (20 g.), and dibenzoyl peroxide (0·6 g.) in carbon tetrachloride (15 c.c.) were heated to 150° for 6 hr. This was done twice and the combined liquid product (182 g.) was distilled. The fraction, b. p. 59—61° (93 g.), was shown by gas chromatography to consist of two main fractions, the second of which had a retention time identical with that of carbon tetrachloride which constituted approximately 20% of the mixture. The first fraction was collected and shown to be *2-chloro-1,2,2-trifluoroethylsulphur pentafluoride* (Found: C, 9·6; F, 59·7. C_2HClF_8S requires C, 9·8; F, 62·1%), $\nu_{max.}$ 1225, 1150, 1075, 1000, 925, 880, 815, 780 cm.$^{-1}$.

Chlorotrifluoroethylene. Sulphur chloride pentafluoride (40 g.), chlorotrifluoroethylene (33 g.), and dibenzoyl peroxide (0·4 g.) in trichlorofluoromethane (30 c.c.) were heated to 100° for 10 hr. On removal of the solvent, the product separated as a wet solid which gave a clear liquid on warming. Distillation yielded a small fraction (2 g.), b. p. 80—83°, which was *2,2-dichlorotrifluoroethylsulphur pentafluoride* (Found: C, 8·3; Cl, 25·2; F, 53·8; S, 11·3%; *M*, 282. $C_2Cl_2F_8S$ requires C, 8·6; Cl, 25·4; F, 54·5; S, 11·5%; *M*, 279), $\nu_{max.}$ 1210s, 420s, 925vs, 900vs, and 765vs cm.$^{-1}$. The bulk of the products boiling above 82° were not further examined.

Hexafluoropropene. Several experiments, in which sulphur chloride pentafluoride and

XUM

hexafluoropropene were heated to 150° in the presence of dibenzoyl peroxide, were carried out. In each case the starting materials, apart from a small handling loss, were recovered.

Dehydrochlorination of 2-Chloro-1,2,2-trifluoroethylsulphur Pentafluoride.—A round-bottom three-neck flask was fitted with a dropping-funnel, a stopper, and a reflux condenser the top of which was connected to a trap cooled to −80°. Light petroleum, b. p. 100—120° (100 c.c.), and the mixture of starting material with carbon tetrachloride (30 g.) were added and brought to a gentle reflux. Finely powdered potassium hydroxide (18 g.) was added through the stoppered opening during 3½ hr., the reaction then appearing to be complete. A colourless liquid (17·5 g.) had collected in the cold trap and was shown by gas chromatography to be pure *trifluorovinylsulphur pentafluoride* (Found: F, 72·4; S, 15·2%; *M*, 206. C_2F_8S requires F, 73·1; S, 15·4%; *M*, 208); the yield, based on 80% purity of the starting material, was 82%. The vapour pressure of this compound accorded with the equation $\log_{10} p = -1310/T + 6{\cdot}36$. The b. p. found by extrapolation was 19°, the latent heat of vaporisation calculated from the slope is 5990 cal. mole^{-1}, and the Trouton constant is 20·5. The infrared absorption spectrum of trifluorovinylsulphur pentafluoride showed intense bands at 1782 (C=C stretching), 1351, 1246, 898vs, δ_{O2}vs, 614 cm.$^{-1}$. No other SF_5 compound was detected.

Photochemical Reactions.—Sulphur chloride pentafluoride and tetrafluoroethylene. The apparatus used was a standard Hanovia 10-l. photochemical reaction vessel with quartz centre tube. This tube acts as a container for a Hanovia 509/12 mercury-arc tube and provides a means of circulating cooling water between the lamp and the reactants. The vessel was evacuated, and filled with sulphur chloride pentafluoride (30 cm. Hg) and tetrafluoroethylene (45 cm. Hg). No reaction took place until the mercury arc was switched on, but then a reaction started which caused a decrease in pressure. The experiment was carried out three times and the liquid products (241 g.) were combined. The gaseous products were shown by gas chromatography to contain three major components whose retention and infrared spectra showed them to be unchanged tetrafluoroethylene,[2] sulphur chloride pentafluoride,[3] and 1,2-dichlorotetrafluoroethylene.[2] The liquid products were distilled and gave fractions (1), b. p. up to 100° (52·5 g.), (2) b. p. 100—150° (75·7 g.), (3) b. p. 150—200° (48·6 g.), and a residue (64·5 g.) which solidified at room temperature. The rise in b. p. was continuous throughout the distillation and each cut taken was shown by gas chromatography to contain several components. By comparing retention times, all the compounds formed in the autoclave reaction of sulphur chloride pentafluoride and tetrafluoroethylene were shown to be present. In addition, disulphur decafluoride [4] was identified by its retention time and infrared spectrum. The extra fractions present in the higher-boiling materials were not identified.

Sulphur chloride pentafluoride and chlorotrifluoroethylene. The 10-l. photochemical reaction vessel was evacuated, filled with sulphur chloride pentafluoride (30 cm. Hg) and chlorotrifluoroethylene (45 cm. Hg), and irradiated for 5 hr. during which more of the reagents in the same molar ratio were added, the total weight used being 190 g. There were obtained 148 g. of a liquid product which was washed with N-potassium hydroxide, water, and saturated brine and dried ($MgSO_4$). The bulk of the material (120 g.) boiled above 150° and was not investigated. The portion boiling below 150° was fractionated, giving: fraction (1) b. p. 26° disulphur decafluoride (2 g.); (2) b. p. 45—49°, 1,2,2-trichlorotrifluoroethane (4 g.); and (3) *1,2-dichlorotrifluoroethylsulphur pentafluoride* (2 g.), b. p. 79·5—82° (Found: C, 8·3; Cl, 25·2; F, 53·8; S, 11·3%; *M*, 282. $C_2Cl_2F_8S$ requires C, 8·6; Cl, 25·4; F, 54·5; S, 11·5%; *M*, 279). The infrared spectrum of the last product differs from that of its 2,2-dichloro-isomer in having intense bands at 1180br,s, 1120s, 1045s, 935s, 895vs, 870s, 815s, 755vs cm.$^{-1}$, but is identical with that obtained (see below) from the reaction of chlorine with trifluorovinylsulphur pentafluoride.

Sulphur chloride pentafluoride and hexafluoropropene. The 10-l. photochemical reaction vessel was filled with an equimolar mixture of sulphur chloride pentafluoride and hexafluoropropene to a total pressure of 1 atm. The mixture was irradiated until there was no further decrease in pressure. There were obtained 54 g. of a colourless liquid which on distillation gave fractions (1), b. p. 25—30° (10 g.) (a mixture of disulphur decafluoride [4] and 1,2-dichlorohexafluoropropane,[2] identified by their infrared spectra), and (2), b. p. 71—73° (15 g.), shown by gas chromatography to contain two almost equal but poorly resolved components which were believed to be 2-chlorohexafluoro-propyl- and the isomeric -isopropyl-sulphur pentafluoride

[2] Simons (ed.), "Fluorine Chemistry," Vol. II, 1954, Academic Press, New York, pp. 469 *et seq.*
[3] Cross, Roberts, Goggin, and Woodward, *Trans. Faraday Soc.*, 1960, **56**, 945.
[4] Dodd, Woodward, and Roberts, *Trans. Faraday Soc.*, 1957, **53**, 1545.

XUM

(Found: C, 11·8; Cl, 11·1; F, 67·5; S, 9·9%; *M*, 310. Calc. for $C_3ClF_{11}S$: C, 11·5; Cl, 11·4; F, 67·0; S, 10·2%; *M*, 312·5). The higher-boiling products gave no clear-cut fractions and were not further investigated.

Chlorination of Perfluorovinylsulphur Pentafluoride.—A 1-l. photochemical reaction vessel was filled with perfluorovinylsulphur pentafluoride (27 cm. Hg) and chlorine (41 cm. Hg). The mixture was irradiated for 30 min. during which the pressure fell by 17 cm. and a liquid product (3 c.c.) was obtained. The excess of chlorine was removed by evaporation. The liquid was found by gas chromatography to have only one major component which was shown by its retention time and infrared spectrum to be the 1,2-dichloro-product.

Discussion

Addition of sulphur chloride pentafluoride to alkenes can proceed by either an ionic or a free-radical mechanism depending on the olefin used. With fluoro-olefins it is necessary to employ a free-radical catalyst to ensure reaction, indicating that, in the cases studied, the addition proceeds by a free-radical mechanism. When benzoyl peroxide is used as the catalyst it is possible to recover chlorobenzene from the products. This suggests that the reaction proceeds by the following stages:

(1) $C_6H_5\cdot + SF_5Cl \longrightarrow C_6H_5Cl + SF_5\cdot$

(2) $SF_5\cdot + C_2H_4 \longrightarrow SF_5\cdot CF_2\cdot CF_2\cdot$

(3) either (*a*) $SF_5\cdot CF_2\cdot CF_2\cdot + C_2F_4 \longrightarrow SF_5\cdot[CF_2]_4\cdot$ (propagation)

or (*b*) $SF_5\cdot CF_2\cdot CF_2\cdot + SF_5Cl \longrightarrow SF_5\cdot CF_2\cdot CF_2Cl + SF_5\cdot$ (chain transfer)

This mechanism accounts for the dependence of the molecular weight on the ratio of sulphur chloride pentafluoride to olefin and for the absence of $Cl\cdot CF_2\cdot CF_2Cl$ in the products which would certainly occur if there were any significant concentration of chlorine atoms present.

The orientation of the product formed in a reaction following this mechanism will depend on the point of attack of the $SF_5\cdot$ radical on the olefin. In this respect this radical appears to behave similarly to the $CF_3\cdot$ radical.[5] Thus with $CF_2{=}CFCl$ the primary attack is on the CF_2 group, leading to the formation of $SF_5\cdot CF_2\cdot CFCl_2$ and higher telomers. The reaction with $CF_2{=}CHF$ is interesting, as the analogy with other molecules suggests that where hydrogen is present radical attack occurs at the carbon atom carrying the most hydrogen, but in molecules derived from tetrafluoroethylene the attack is on the CF group. In this case the primary attack appears to be on the CHF group leading to $SF_5\cdot CHF\cdot CF_2Cl$. With hexafluoropropene there is no reaction under these conditions, which must mean that the $SF_5\cdot$ radical is insufficiently reactive to add to this olefin.

In the photochemical reaction the initial step is the homolysis of the SF_5Cl molecule to give an SF_5 radical and a Cl atom; from the results obtained it appears that the latter is very much more reactive than the former. Thus $CF_3\cdot CF{:}CF_2$ is found to react photochemically with SF_5Cl where both $SF_5\cdot$ radicals and $Cl\cdot$ atoms are present but fails to react in the presence of a peroxide where only $SF_5\cdot$ radicals are produced. In this case the primary process is probably the reaction

(4) $Cl\cdot + CF_3\cdot CF{:}CF_2 \xrightarrow{a} CF_3\cdot CFCl\cdot CF_2\cdot$

$\xrightarrow{b} CF_3\cdot \dot{C}F\cdot CF_2Cl$

followed by either further reaction with SF_5Cl to give $CF_3\cdot CFCl\cdot CF_2Cl$ in each case or reaction with $SF_5\cdot$ radicals to give a mixture of $SF_5\cdot CF_2\cdot CFCl\cdot CF_3$ and $SF_5\cdot CF(CF_3)\cdot CF_2Cl$. This production of a pair of isomers in an addition reaction is somewhat unusual and implies that in this case the $Cl\cdot$ is too reactive to discriminate between the two possible reaction sites. In the case of $CF_2{:}CF_2$ where the two reaction sites are identical this effect is not observed.

[5] Haszeldine and Steele, *J.*, 1953, 1592.

XUM

With chlorotrifluoroethylene only a single addition product is obtained which must mean that in this case attack by Cl· takes place at one reaction site very much more readily:

(5) $Cl\cdot + CF_2{:}CFCl \longrightarrow Cl{\cdot}CF_2{\cdot}CFCl\cdot$

which can either lead to polymer formation with more $CF_2{:}CFCl$, abstract chlorine from SF_5Cl, or react with an SF_5 radical to give $CF_2Cl{\cdot}CFCl{\cdot}SF_5$. It is curious that the chlorine atoms should be selective here but not with $CF_3{\cdot}CF{:}CF_2$.

IMPERIAL CHEMICAL INDUSTRIES LIMITED,
ALKALI DIVISION RESEARCH DEPARTMENT,
WINNINGTON, NORTHWICH, CHESHIRE.

[*Received, October 5th*, 1960.]

---

395. *The Ultraviolet Absorption of Isolated Double Bonds.*

By J. H. CHAPMAN and A. C. PARKER.

The ultraviolet absorptions of thirty substances, mostly steroids and triterpenes, containing isolated double bonds have been measured at wavelengths down to 187 mμ.

Structural correlations are discussed in the light of these and other workers' results.

RECENTLY several workers have reported measurements of absorption spectra in the ultraviolet region below 205 mμ, made principally on steroids and triterpenes, with the purpose of distinguishing between isolated double bonds having various degrees of substitution. Turner,[1] using a vacuum spectrometer with fluorite optics, concluded that, with few exceptions, di-, tri-, and tetra-substituted double bonds could be differentiated satisfactorily by such measurements. Ellington and Meakins [2] have since reported their examination of a similar collection of compounds in a commercial instrument with silica optics and came to much less favourable conclusions. Stich *et al.*[3] made similar measurements on another commercial instrument and came to substantially the same conclusions as Turner.

We were interested in the possibility of applying the results of measurements in this region on a standard commercial spectrophotometer to the determination of structure and have therefore attempted to clarify this situation by examining a smaller but representative group of compounds, including those examined by earlier workers as far as they were available.

EXPERIMENTAL

The spectra were measured on a standard Hilger Uvispek model 308 spectrophotometer fitted with a silica prism and flushed before use with " white spot " nitrogen until the energy at 187 mμ reached a constant (maximum) value. The percentage of stray light under these conditions was determined by means of a Vycor filter.[4] The figures in Table 1 therefore refer to

TABLE 1.

λ (mμ)	185	190	195
Stray light (%)	1·2	0·12	0·06

stray light of wavelengths greater than 220 mμ. These figures are so low (cf. ref. 3) that we considered it unnecessary to correct our observations for stray light, particularly as solutions were used that in general had a transmission greater than 50% at $\lambda_{max.}$; it was thought that the

[1] Turner, *J.*, 1959, 30, where reference are given to earlier papers.
[2] Ellington and Meakins, *J.*, 1960, 697.
[3] Stich, Rotzler, and Reichstein, *Helv. Chim. Acta*, 1959, **42**, 1480.
[4] Gibson in Mellon's " Analytical Absorption Spectroscopy," Wiley, New York, 1950, p. 247.

XUM

TABLE 2.*

Compound	This work λ (mμ)	This work ε	Ellington & Meakins [2] λ (mμ)	Ellington & Meakins [2] ε	Stich *et al.*[3] λ (mμ)	Stich *et al.*[3] ε	Turner [1] λ (mμ)	Turner [1] ε	Other workers λ (mμ)	Other workers ε
Disubstituted										
Cyclohexene	<187	(6000)			<190	7200			183·5 [d]	7400 [d]
11α-Acetoxy-3β-hydroxy-5α-ergost-22-ene	<187	(14,000)								
3β-Acetoxy-5α-ergost-22-ene							186	11,600		
5α-Cholest-2-ene [a]	<187	(7000)	189	5100	189·5	5600	182	7500		
3β-Acetoxy-5α-cholest-6-ene [b]	<188	(8000)								
5α-Cholest-6-ene			*195*	*7500*	190·5	7800				
5α,22α-Spirost-2-ene	<187	(7000)								
3β-Hydroxy-5α,22α-spirost-11-ene	<187	(6000)								
Lupeol acetate	195	9000	194	9300			196	8450		
Lupeol [a]	*197*	*8000*	*195*	*8900*						
Trisubstituted										
2,4,4-Trimethylpent-1-ene	193	7000								
2,4,4-Trimethylpent-2-ene	193·5	8000								
Cholest-5-ene [a]	190	9000	191	8200	193	8100	190	7820		
3β-Hydroxycholest-5-ene									187 [d]	15,800 [d]
									191 [e]	10,200 [e]
3β-Acetoxycholest-5-ene	189	8000	195	8100	193	8900				
3β,24-Diacetoxycholest-5-ene [b]	190	12,000								
5α-Cholest-4-ene [b]	192	10,000	*196*	*9700*	194	10,700	190	8860		
3β,5α-Diacetoxyergost-7-en-11-one	187	12,000								
Tetrasubstituted										
3β-Acetoxylanost-8-ene	202	9000	197	7500			202	7000		
3β-Hydroxylanost-8-ene	*201*	*7000*	*198*	*7300*						
3β-Acetoxy-5α-ergost-8(14)-ene	*200*	*11,000*	*204*	*12,200*	*205*	*11,800*			206 [e]	11,200 [e]
3β-Acetoxy-5α-hydroxy-ergost-8(9)-ene	*200*	*9000*								
3β-Acetoxy-11-methyl-5α,25β-spirost-9(11)-ene	200	7000								
Euphenyl acetate [c]	197	10,000	197	8400			200	10,400		
Saturated steroids and ketones										
3β-Acetoxy-5α-cholestane	≪187	300 †								
3β-Hydroxy-5α-cholestane			No max.	300 †						
Acetone	186—187	2000			191	1000			186 [d]	5800 [d]
2,4,6-Trimethylcyclohexanone	<187	(1000)								
2,2,6,6-Tetramethylcyclohexanone	<187	(1000)								
Cholestan-3-one	<187	(2500)	*194*	*1600*	188·5	2000				
3β-Acetoxy-5α-ergostan-11-one	<187	(3000)								
3β-Acetoxy-5α,9β-ergostan-11-one	<187									
3β-Acetoxy-5α-pregnan-12-one	<187	(3000)								
3β-Acetoxy-5α-pregnan-20-one	<187	(4000)								

* Entries in italics indicate the use of ethanol as solvent; otherwise hydrocarbon solvents were used.

† Relates to ε_{198}.

a, *b*, *c*. We are indebted to Prof. D. H. R. Barton for specimens marked *a*, to Prof. H. B. Henbest for those marked *b*, and to Dr. G. D. Meakins for those marked *c*.

d, *e*. These figures are quoted by Stich *et al.*[3] from measurements made by (*d*) Klevens and Platt, (*e*) the Shell Development Laboratories, Wood River, Ill., U.S.A.

slight loss of accuracy occasioned by the measurement of small E values would be more than offset by consequently minimising the effect of stray light.

All measurements were made in 1-mm. demountable silica cells (Hilger and Watts). Below 220 mμ these were not accurately matched. Determinations of the correction necessary showed this to be variable but fortunately small: it depended on the position in which the silica components were reassembled, and perhaps also on surface contamination, and would therefore have been difficult to apply when a demountable cell was in use. Also slight evaporation could not be avoided when hexane was used, and for these reasons the values of ε are given to one significant figure only.

A commercial " spectroscopic " grade of n-hexane and absolute ethanol were used. With these solvents readings could be made to 187 and 195 mμ, respectively.

Results and Discussion

The values found for $\lambda_{max.}$ and $\varepsilon_{max.}$ are given in Table 2. When no maximum was reached within the range of the present series of measurements, the values of ε at 188 and 195 mμ (for hexane and ethanol, respectively) are given in parentheses. When available, the values obtained by other workers for the same or closely related compounds are included for comparison.

Also included in Table 2 are several saturated ketones and 3β-acetoxycholestane, none of which showed a maximum at wavelengths $\geqslant$187 mμ in n-hexane.

Our results, like Turner's, clearly fall into three groups that coincide with the three degrees of substitution of the double bonds in the compounds concerned (Table 3). We find also the same exceptions, *viz.*, a bathochromic shift associated with the geminally disubstituted double bond in lupeol, and a shift from the expected position for a Δ^7-bond: here we agree with Stich *et al.* in finding this to be to a shorter wavelength.

Table 3.

No. of substituents	2	3	4
$\lambda_{max.}$ (mμ)	187	187—193	199—202

In seeking to explain the discrepancy between the results obtained by Turner and by ourselves (and to a considerable extent, by Stich, Rotzler, and Reichstein) on the one hand, and, on the other, by Ellington and Meakins (a discrepancy clearly in the instrumental results and not in their interpretation), we conclude that the last workers have underestimated the effect of stray light on measurements made in ethanol. The transmission of 1 mm. of absolute ethanol at 195 mμ is less than 10% and drops to 1% at 192 mμ. In this way a situation can readily be envisaged in which, despite the linearity up to an optical density of 1·8 at 195 mμ, artificial maxima will be produced between 190 and 195 mμ, with corresponding shifts to longer wavelengths of true maxima in this region. The spurious effects produced by scattered light are dependent on its intensity relative to that of the transmitted light being measured, *i.e.*, the E of the solution being examined. Thus the assertion that the compounds containing neither C=C nor C=O bonds showed no bands has little significance for the apparent spectra of the substances we are interested in.

The Swiss group have examined more closely the effect of stray light in their measurements and have made a correction for it, and, in their tables, indicate corrected wavelengths. Nevertheless, discrepancies exist between their reported values of $\lambda_{max.}$ and those given by Turner and ourselves for similar groupings; in particular, those for disubstituted olefins tend to be at longer wavelengths. Though claiming reasonable agreement of their results with those from the Shell Development Laboratories, they note the much poorer agreement with Platt, Klevens, and Price,[5] but do not attempt to explain this.

We conclude that measurements made with an instrument having a low level of intrinsic scattered light down to 187 mμ, on solutions of low (*ca.* 0·3) optical density, for

[5] Platt, Klevens, and Price, *J. Chem. Phys.*, 1949, **17**, 466.

XUM

classification of double bonds according to the degree of substitution, give results in close agreement with those obtained on a vacuum-fluorite instrument. This procedure, moreover, would seem to give rather better results than that of applying a correction to measurements involving a larger contribution from scattered light.

GLAXO LABORATORIES, LTD., GREENFORD, MIDDLESEX. [*Received, October 18th*, 1960.]

---

396. *Complexes of Tetrahydrothiophen Oxide.*

By RONALD FRANCIS and F. ALBERT COTTON.

The co-ordination chemistry of tetrahydrothiophen oxide with a variety of metal salts as acceptors has been investigated. New complexes have been isolated and characterized by analytical, magnetic, and spectral data. The stoicheiometric and stereochemical relationships parallel those with dimethyl sulphoxide.

WE have recently reported the preparation and characterization of a variety of complexes containing dimethyl sulphoxide as donor.[1-3] Our studies have been extended to the ligand behaviour of other sulphoxides, and in this paper we describe some complexes formed by the cyclic sulphoxide, tetrahydrothiophen oxide $[CH_2]_4{>}SO$ (referred to in formulæ below as Tpo). It was expected that despite the presence of a larger hydrocarbon residue bonded to the sulphur, the locking of the methylene groups in the ring would have a compensatory effect, making this sulphoxide at least as good a donor as dimethyl sulphoxide. Consistently with this we have found that metal salts generally are highly soluble in tetrahydrothiophen oxide and that the isolation of well-defined complexes is relatively easy.

It is evident from the types of complexes obtained and their properties that tetrahydrothiophen oxide has ligand behaviour fundamentally similar to that of dimethyl sulphoxide. The complex with boron trifluoride is analogous to those formed by dimethyl sulphoxide [1] and by n-dodecyl ethyl sulphoxide.[4] The ferric chloride and stannic chloride complexes possess the same high thermal stability as their dimethyl sulphoxide analogues.

The infrared data recorded in Table 1 are subject to the same interpretation as was previously developed [2] for dimethyl sulphoxide complexes, and they indicate that co-

TABLE 1. *Infrared data for some tetrahydrothiophen oxide complexes.*

Compound	S–O Stretching frequency (cm.$^{-1}$)	Compound	S–O Stretching frequency (cm.$^{-1}$)
C_4H_4S(Tetrahydrothiophen) [a] ...	No significant bands 650—1200 cm.$^{-1}$	$[Co(Tpo)_6](CoI_4)$ [d]	965s
C_4H_4SO(Tpo) [a]	1010s [a]	$[Ni(Tpo)_6](NiCl_4)$ [b] ...	971s
$[Co(Tpo)_6](ClO_4)_2$ [b]	963s	$[Ni(Tpo)_4]Br_2$ [c]	970s
$[Co(Tpo)_6](CoCl_4)$ [b].....	965s	$[Ni(Tpo)_4]I_2$ [d].....	945s
$[Co(Tpo)_6]Br_2$ [c]	967s	$[Cu(Tpo)_2Cl_2]$ [b]	937s
$[Co(Tpo)_6](CoBr_4)$ [c]	966s	$[Pd(Tpo)_2Cl_2]$ [b]	1127s †
$[Co(Tpo)_6]I_2$ [d]	963s	$[Pt(Tpo)_2Cl_2]$ [b]	1155 ‡

[a] 10% solution in $CHCl_3$. [b] Pressing in KCl. [c] Pressing in KBr. [d] Pressing in KI.
[a] Also 1150mw, 1092m, 660m. † Also 1140sh, 1068s. ‡ Also 1140m, 1130m, 1087m, 1077m.

ordination takes place through the oxygen atom in all cases except for the palladium(II) and platinum(II) complexes, where it appears that the sulphur atom is bound to the metal. With tetrahydrothiophen oxide, the steric argument in favour of oxygen co-ordination in the hexakis(tetrahydrothiophen)metal(II or III) ions is, of course, even more cogent than for the analogous species containing dimethyl sulphoxide.

[1] Cotton and Francis, *J. Amer. Chem. Soc.*, 1960, **82**, 2986.
[2] Cotton, Francis, and Horrocks, *J. Phys. Chem.*, 1960, **64**, 1534.
[3] Cotton and Francis, *J. Inorg. Nuclear Chem.*, in the press.
[4] Laughlin, *J. Org. Chem.*, 1960, **25**, 864.

XUM

The cobalt and nickel complexes of tetrahydrothiophen oxide show the same stereochemical tendencies as do those of dimethyl sulphoxide [1,3] as comparison of the formulæ, properties, and interconversion sequences in the two series of compounds clearly shows. It seems safe to presume from their colours and evident stoicheiometric relations to the corresponding dimethyl sulphoxide compounds [1,3] that the tetrahydrothiophen oxide compounds may be assigned structures in the following way.

For $CoCl_2$,3Tpo, the structure should be $[Co(Tpo)_6][CoCl_4]$, in which the cation contains cobalt(II) octahedrally co-ordinated by oxygen atoms and the tetrachlorocobaltate(II) ion is, of course, tetrahedral. The apparent magnetic moment of the cobalt(II) in this compound, 4·89 B.M. at 28°, agrees with that previously reported for $CoCl_2$,3DMSO.[1,3] Similarly, there seems little doubt that $CoBr_2$,6Tpo and $CoBr_2$,3Tpo are correctly formulated as $[Co(Tpo)_6]Br_2$ and $[Co(Tpo)_6][CoBr_4]$, and CoI_2,6Tpo and CoI_2,3Tpo as $[Co(Tpo)_6]I_2$ and $[Co(Tpo)_6][CoI_4]$. The red colour of $Co(SCN)_2$,4Tpo indicates that it does not contain tetrahedrally co-ordinated cobalt(II) although the deep blue solution from which it crystallizes evidently does; octahedral, $[Co(Tpo)_4(SCN)_2]$, or planar, $[Co(Tpo)_4](SCN)_2$, structures are possible. The deep blue $Co(SCN)_2$,3Tpo is doubtless correctly formulated as $[Co(Tpo)_6][Co(NCS)_4]$. $[Co(Tpo)_6](ClO_4)_2$ has the high magnetic moment (Table 2) typical of many octahedral cobalt(II) compounds, as does $[Co(DMSO)_6](ClO_4)_2$.

TABLE 2. *Magnetic data for several complexes containing tetrahydrothiophen oxide.*[a]

Compound	$\chi^{corr.}$ (c.g.s. units × 10^6)	Diamag. (corr.) (c.g.s. units × 10^6)	Temp. (° K)	$\mu^{(eff.)}$ [b] (B.M.)
$[Co(C_4H_8SO)_6](ClO_4)_2$	10,420	−438	301	5·03
$[Co(C_4H_8SO)_6][CoCl_4]$	9930	−240	301	4·89
$[Ni(C_4H_8SO)_6][NiCl_4]$	5720	−240	295	3·69
$NiBr_2$,4C_4H_8SO	5950	−323	296	3·77

[a] Molar susceptibilities are for a formula unit containing one metal ion, *e.g.*, for $[Co(C_4H_8SO)_6][CoCl_4]$ for the formula unit $CoCl_2$,3C_4H_8SO, and effective moments are per metal atom. [b] Calc. from the Curie equation.

The compounds $[Ni(Tpo)_6](ClO_4)_2$, $[Ni(Tpo)_6][NiCl_4]$, $[Ni(Tpo)_6]Br_2$, $[Ni(Tpo)_6][NiBr_4]$, $NiBr_2$,4Tpo, $[Ni(Tpo)_6]I_2$, NiI_2,4Tpo, and $Ni(SCN)_2$,4Tpo all have their dimethyl sulphoxide analogues. No dimethyl sulphoxide analogue of $[Ni(Tpo)_6]Cl_2$ was isolated, but it might be possible to do so; no particular attempt has been made by us. Once again the tetrahedral tetrachloronickelate(II) and tetrabromonickelate(II) ions are formed. The high mean magnetic moment of the nickel atoms in $[Ni(Tpo)_6][NiCl_4]$ gives definite confirmation of this, as shown previously [1,3] for the analogous dimethyl sulphoxide compound. The pale green colour of $Ni(SCN)_2$,4Tpo shows that this compound, like its dimethyl sulphoxide analogue,[3] does not contain tetrahedral nickel(II). Again in this series of compounds we obtain a bromide of the stoicheiometry $NiBr_2$,4 sulphoxide, which is blue and appears to contain all or some of its nickel ions in tetrahedral co-ordination. The magnetic moment of 3·77 BM supports this view, as does the appearance of the reflectance spectrum, which very closely resembles that of $NiBr_2$,4DMSO.

EXPERIMENTAL

In formulæ, Tpo denotes tetrahydrothiophen oxide.

Compound BF_3,Tpo.—Gaseous boron trifluoride was passed into a benzene solution of tetrahydrothiophen oxide (Wateree Chemical Co., Lugoff, S. C.). An exothermic reaction occurred and, on cooling, colourless crystals of the *complex* separated. These were sublimed at 65° in a good vacuum (Found: C, 27·9; H, 4·8. $C_4H_8BF_3OS$ requires C, 27·9; H, 4·7%).

Compound $FeCl_3$,2Tpo.—Tetrahydrothiophen oxide was added dropwise to an ether solution of anhydrous (sublimed) ferric chloride, producing an immediate yellow precipitate; this *product* was filtered off, dried by pumping at room temperature, and sublimed at 170° in a good vacuum (Found: C, 25·5; H, 2·9. $C_8H_{16}Cl_2FeO_2S_2$ requires C, 25·9; H, 4·4%).

XUM

Compound $CuCl_2$,2Tpo.—Cupric chloride was dissolved in a 5 molar excess of warm tetrahydrothiophen oxide to give a green solution. Green crystals of the *salt*, which were slowly deposited, were separated and dried in vacuum at 55° (Found: C, 28·0; H, 4·8; Cl, 20·6; Cu, 18·5. $C_8H_{16}Cl_2CuO_2S_2$ requires C, 28·0; H, 4·7; Cl, 20·7; Cu, 18·5%).

Compound $SnCl_4$,2Tpo.—Tetrahydrothiophen oxide was added dropwise to undiluted stannic chloride, giving a white precipitate of *complex* which was filtered and sublimed at 210° in a high vacuum (Found: C, 20·3; H, 3·3. $C_8H_{16}Cl_4O_2S_2Sn$ requires C, 20·5; H, 3·4%).

Compound $PdCl_2$,2Tpo.—Palladium chloride was dissolved in about a 5-molar excess of warm tetrahydrothiophen oxide. From the yellow solution, a brown crystalline *product* separated on storage. It was dried in a vacuum at 55° (Found: C, 25·3; H, 4·3. $C_8H_{16}Cl_2O_2PdS_2$ requires C, 24·9; H, 4·2%).

Compound $PtCl_2$,2Tpo.—Tetrahydrothiophen oxide was added dropwise with agitation to a concentrated aqueous solution of hydrogen tetrachloroplatinate(II), warmed to 60°, until the deep red-orange colour was discharged to a light yellow. The volume was then reduced in a vacuum-desiccator until fine, pale yellow crystals of the *complex* separated. These were separated, twice recrystallized from water, and dried in a vacuum (Found: C, 20·4; H, 3·5. $C_8H_{16}Cl_2O_2PtS_2$ requires C, 20·2; H, 3·4%).

Compound $CoCl_2$,3Tpo.—Anhydrous cobaltous chloride was dissolved in a 10 molar excess of tetrahydrothiophen oxide to give a dark blue solution from which dark blue crystals of the *product* were obtained on removal of excess of tetrahydrothiophen oxide in a vacuum (Found: C, 32·7; H, 5·5; Cl, 16·0; Co, 13·3. $C_{12}H_{24}Cl_2CoO_3S_3$ requires C, 32·6; H, 5·5; Cl, 16·0; Co, 13·3%).

Compounds $CoBr_2$,6Tpo *and* $CoBr_2$,3Tpo.—Anhydrous cobaltous bromide dissolved in tetrahydrothiophen oxide to give a pink solution from which a pink crystalline product, *hexakis(tetrahydrothiophen oxide)cobalt*(II) *dibromide* (Found: C, 34·0; H, 5·7. $C_{24}H_{48}Br_2CoO_6S_6$ requires C, 34·2; H, 5·7%), separated when the solution was kept over phosphorus pentoxide. This complex was filtered off and dried in a vacuum at room temperature. When heated in a vacuum at 60° the pink substance loses tetrahydrothiophen oxide immediately, and a light blue powder, *tris(tetrahydrothiophen oxide)cobalt*(II) *dibromide*, is obtained (Found: C, 27·2; H, 4·7. $C_{12}H_{24}Br_2CoO_3S_3$ requires C, 27·1; H, 4·6%).

Compounds CoI_2,6Tpo *and* CoI_2,3Tpo.—Anhydrous cobaltous iodide was dissolved in tetrahydrothiophen oxide to give a pale yellow solution which became red-orange on concentration over phosphorus pentoxide in a vacuum. Deep red crystals of *hexakis(tetrahydrothiophen oxide)cobalt*(II) *iodide* separated (Found: C, 30·5; H, 5·1. $C_{24}H_{48}CoI_2O_6S_6$ requires C, 30·7; H, 5·2%). They were filtered off and dried in a vacuum at room temperature. In a vacuum at 60° they readily lost tetrahydrothiophen oxide, affording dark green *tris(tetrahydrothiophen oxide)cobalt*(II) *iodide* (Found: C, 23·0; H, 3·6. $C_{12}H_{24}I_2CoO_3S_3$ requires C, 23·0; H, 3·8%).

Compounds $Co(SCN)_2$,4Tpo *and* $Co(SCN)_2$,3Tpo.—Hexa-aquocobalt(II) thiocyanate was dissolved in a ten-fold molar excess of tetrahydrothiophen oxide, giving a pink solution. When kept over phosphorus pentoxide in a vacuum, this solution slowly became dark blue, while red crystals of *tetrakis(tetrahydrothiophen oxide)cobalt*(III) *dithiocyanate* separated. These were filtered off and dried in a vacuum at room temperature (Found: C, 26·8; H, 5·4. $C_{18}H_{32}CoN_2O_4S_6$ requires C, 36·5; H, 5·4%). In a vacuum at 60°, they lost tetrahydrothiophen oxide, affording dark blue *tris(tetrahydrothiophen oxide)cobalt*(II) *dithiocyanate* (Found: C, 34·3; H, 4·9. $C_{14}H_{24}CoN_2O_3S_5$ requires C, 34·5; H, 5·0%).

Compound $Co(ClO_4)_2$,6Tpo.—Hexa-aquocobalt(II) perchlorate was dissolved in tetrahydrothiophen oxide to give a pink solution. On removal of the excess of tetrahydrothiophen oxide in a vacuum, pink crystals of the *complex* were obtained (Found: C, 32·51; H, 5·45; Co, 6·7. $C_{24}H_{48}Cl_2CoO_{14}S_6$ requires C, 32·6; H, 5·5; Co, 6·7%).

Compounds $NiCl_2$,6Tpo *and* $NiCl_2$,3Tpo.—Anhydrous nickel chloride was dissolved in a ten-fold molar excess of tetrahydrothiophen oxide to give a pale green solution. On storage of this over phosphorus pentoxide in a vacuum, green crystals of *hexakis(tetrahydrothiophen oxide)nickel*(II) *dichloride* were deposited. These were filtered off and dried over phosphorus pentoxide in a vacuum at room temperature (Found: C, 38·5; H, 6·5. $C_{24}H_{48}Cl_2NiO_6S_6$ requires C, 38·2; H, 6·4%). In a vacuum at 60°, these crystals lost tetrahydrothiophen oxide, affording *tris(tetrahydrothiophen oxide)cobalt*(II) *dichloride* as a light blue-green powder (Found: C, 32·6; H, 5·7. $C_{12}H_{24}Cl_2NiO_3S_3$ requires C, 32·6; H, 5·47%).

XUM

Compounds $NiBr_2$,6Tpo, $NiBr_2$,4Tpo, *and* $NiBr_2$,3Tpo.—Anhydrous nickel bromide was dissolved in a ten-fold molar excess of tetrahydrothiophen oxide to give a light green solution which, when kept over phosphorus pentoxide in a vacuum, deposited green crystals of *hexakis(tetrahydrothiophen oxide)nickel*(II) *dibromide* (Found: C, 33·7; H, 5·3. $C_{24}H_{48}Br_2NiO_6S_5$ requires C, 34·2; H, 5·7%). This rather easily loses tetrahydrothiophen oxide on long standing to give light blue *tetrakis(tetrahydrothiophen oxide)nickel*(II) *dibromide* (Found: C, 30·0; H, 5·0. $C_{16}H_{32}Br_2NiO_4S_4$ requires C, 30·2; H, 5·1%). On prolonged heating at 80° in a vacuum, both of the foregoing compounds lose tetrahydrothiophen oxide to give dark green *tris(tetrahydrothiophen oxide)nickel*(II) *dibromide* (Found: C, 27·4; H, 4·6. $C_{12}H_{24}Br_2NiO_3S_3$ requires C, 27·1; H, 4·6%).

Compounds NiI_2,6Tpo *and* NiI_2,4Tpo.—Anhydrous nickel iodide was dissolved in tetrahydrothiophen oxide to give a pale orange solution which deposited light green crystals of hexakis(tetrahydrothiophen oxide)nickel(II) iodide on storage over phosphorus pentoxide in a vacuum. The analytical figures for this substance approximated to those required by the above formula, but were always somewhat low in carbon and hydrogen owing to the instability of the compound. When these green crystals were kept in air or were heated at 60° in a vacuum, they readily lost tetrahydrothiophen oxide, affording the red-orange compound *tetrakis(tetrahydrothiophen oxide)nickel*(II) *di-iodide* (Found: C, 26·1; H, 4·1. $C_{16}H_{32}I_2NiO_4S_4$ requires C, 26·4; H, 4·4%).

Compound $Ni(SCN)_2$,4Tpo.—Hydrated nickel thiocyanate was dissolved in tetrahydrothiophen oxide to give a light green solution which deposited a *complex* as light green crystals when kept over phosphorus pentoxide in a vacuum. No other definite compound was obtained on heating these green crystals in a vacuum (Found: C, 36·6; H, 5·3. $C_{18}H_{32}N_2NiO_4S_6$ requires C, 36·5; H, 5·4%).

Compound $Ni(ClO_4)_2$,6Tpo.—Hexa-aquonickel(II) perchlorate was dissolved in tetrahydrothiophen oxide, giving a green solution which afforded light green crystals of a *complex* when excess of tetrahydrothiophen oxide was distilled off in a vacuum (Found: C, 32·7; H, 5·4. $C_{24}H_{48}Cl_2NiO_{14}S_6$ requires C, 32·7; H, 5·5%).

All physical measurements were made as previously described.[1-3]

We are grateful to the United States Atomic Energy Commission for financial support under Contract No. AT(30-1)-1965.

DEPARTMENT OF CHEMISTRY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
CAMBRIDGE 39, MASSACHUSETTS, U.S.A. [*Received, October 26th*, 1960.]

---

397. *The Preparation of Mixed Pinacols by Cathodic Reduction. Part II.*[1]

By M. J. ALLEN, W. G. PIERSON, and (MISS) J. A. SIRAGUSA.

The electrochemical preparation of 2-*p*-aminophenyl-3-*p*-chlorophenyl-, 2-*p*-methoxyphenyl-3-3′-pyridyl-, 2-*p*-chlorophenyl-3-3′-pyridyl-, and 2-phenyl-3-3′-pyridyl-butane-2,3-diol is described. The last two pinacols were converted into their corresponding indenes. The nitration and subsequent reduction of the 1-methyl-2-3′-pyridylindene yielded 5-amino-1-methyl-2-3′-pyridylindene.

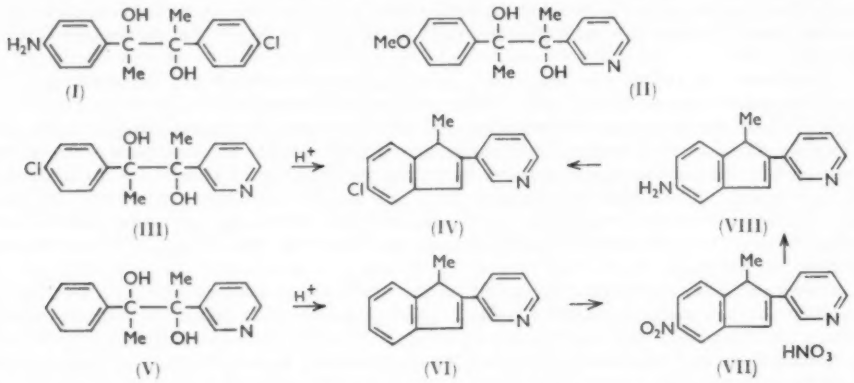
THE studies to be described were undertaken with the object of preparing some new pinacols which might lead to compounds of therapeutic value. It was known as early as 1950 that the pinacol from 4-aminoacetophenone,[2] on treatment with dilute hydrochloric acid, yielded the biologically active pinacone, 3,3-di-*p*-aminophenylbutan-2-one dihydrochloride [3] (referred to as Amphenone B in biological literature [4]). Since then a

[1] Part I, Allen, Siragusa, and Pierson, *J.*, 1960, 1045.
[2] Allen and Corwin, *J. Amer. Chem. Soc.*, 1950, **72**, 114.
[3] Allen and Corwin, *J. Amer. Chem. Soc.*, 1950, **72**, 114; Bencze and Allen, *J. Org. Chem.*, 1957, **22**, 352.
[4] Chart and Sheppard, *J. Medicin. Pharmaceut. Chem.*, 1959, **1**, 407.

XUM

number of pinacones and indenes derived from pinacols have demonstrated this Amphenone-like activity.[5]

The pinacols in this study were obtained by reductive coupling of 4-amino- with 4-chloro-acetophenone, and of acetophenone, 4-chloroacetophenone, and 4-methoxyacetophenone with 3-acetylpyridine. These mixed pinacols were separated from their companion symmetrical pinacols by chromatography on alumina or solvent-distribution. The



various attempts to rearrange 2-*p*-aminophenyl-3-*p*-chlorophenylbutane-2,3-diol (I) and 2-*p*-methoxyphenyl-3-3′-pyridylbutane-2,3-diol (II) to the corresponding pinacones or to dehydrate them to the corresponding indenes resulted in unworkable tars. Although infrared data indicated the presence of both conjugated and unconjugated carbonyl groups after rearrangement of 2-*p*-chlorophenyl- (III) and 2-phenyl-3-3′-pyridylbutane-2,3-diol (V), yields were apparently too small to permit isolation. It was possible, however, to isolate the corresponding indenes (IV and VI) from the reaction mixtures in fairly satisfactory yields.

The indene structure assigned to (IV) was arrived at from ultraviolet spectra and from infrared data in which the band present at 815 cm.$^{-1}$ also indicated a trisubstituted benzene ring. A mechanism previously proposed[6] for the formation of indenes by dehydration of pinacols would place the chloro-group in the 6-position.

It was of further interest to prepare 5-amino-1-methyl-2-3′-pyridylindene (VIII). This was accomplished by nitration of 1-methyl-2-3′-pyridylindene (VI) followed by reduction. The position of the amino-group was verified by its conversion into a chloro-substituent by a Sandmeyer reaction to yield 5-chloro-1-methyl-2-3′-pyridylindene (IV).

Experimental

The electrolysis cells,[7] and the Redoxotrol[8] used for the controlled potential reductions, have been described previously. The reference potentials used in the experiments were obtained from voltammetric curves.

Cathodic Reductions.—The catholyte consisted of equimolar quantities of each ketone. The anolyte was a 40% aqueous potassium carbonate solution. All reactions were performed at the b. p. (82—83°). The other experimental details are outlined in the Table, the reactants being (*a*) 4-amino- (2·7 g.) and 4-chloro-acetophenone (3·09 g.), (*b*) 3-acetylpyridine (9·68 g.) and 4-methoxyacetophenone (12·08 g.), (*c*) 3-acetylpyridine (57·42 g.) and 4-chloroacetophenone (73·28 g.), and (*d*) 3-acetylpyridine (57·42 g.) and acetophenone (57·19 g.), together

[5] Bencze and Allen, *J. Medicin. Pharmaceut. Chem.*, 1959, **1**, 395.
[6] Allen and Corwin, *J. Amer. Chem. Soc.*, 1950, **72**, 114.
[7] Allen and Cohen, *J. Amer. Electrochem. Soc.*, 1959, **106**, 451.
[8] Allen, "Organic Electrode Processes," Chapman & Hall, 1958, pp. 24—28; *Canad. J. Chem.*, 1959, **37**, 257.

with (in order, *a*, *b*, *c*, *d*) potassium acetate 15, 60, 354, 354 g., ethanol 25, 100, 590, 590 ml., and water 17, 68, 402, 402 ml.

Catholyte	(*a*)	(*b*)	(*c*)	(*d*)
Reference potential (v) vs. S. C. E. ...	−1·8	−1·80	−1·84	−2·0
Cathode area (cm.²)	17·2	52·0	112·2	112·2
Initial amperage	6·4	17·0	17·0	17·5
Final amperage	0·2	0·4	2·9	2·4
Initial applied voltage	8·5	19·5	11·2	13·0
Final applied voltage	2·6	3·0	4·0	6·1
Electrolysis time (min.) to current plateau	32	80	283	230
Coulombs passed	2974 (77%)	15,396 (99·7%)	118,000 (128%)	123,900 (135%)
Approx. yield of mixed pinacol based on analytical data obtained on basic fraction	9·1	18·9	30·0	19·2
Yield of product isolated	4·7	2·9	25·8	10·9

Isolation of Pinacols.—(a) 2-p-*Aminophenyl*-3-p-*chlorophenylbutane*-2,3-*diol* (I). The catholyte was evaporated under reduced pressure to remove the alcohol and then acidified with hydrochloric acid. The acidified solution was exhaustively extracted with methylene chloride, made basic with aqueous potassium hydroxide, saturated with potassium chloride, and extracted with methylene chloride. These extracts were dried (Na_2SO_4) and evaporated to dryness. The resultant brown solid was dissolved in benzene (135 ml.) and placed on a neutral alumina column (Woelm; activity 3; 135 g.). The column was eluted with benzene (15 × 135 ml.) and then with 3 : 1 benzene–ether (5 × 135 ml.). The benzene–ether fractions were combined, evaporated to dryness, redissolved in benzene (30 ml.), and rechromatographed on neutral alumina (30 g.). The column was eluted with benzene (25 × 30 ml.). Fractions 11—25 gave a white crystalline material which on recrystallization from cyclohexane gave the pinacol (0·28 g.), m. p. 135—137° (Found: C, 65·9; H, 6·15; N, 4·8. $C_{16}H_{15}ClNO_2$ requires C, 65·9; H, 6·2; N, 4·8%).

(b) 2-p-*Methoxyphenyl*-3-3′-*pyridylbutane*-2,3-*diol* (II). After distillation of the alcohol from the catholyte the remaining mixture of an oil and aqueous fraction was chilled. The oil was separated, dissolved in butyl alcohol, and extracted a number of times with N-hydrochloric acid. The acid extracts were made basic with 2N-potassium hydroxide, saturated with sodium chloride, and extracted with butyl alcohol. These extracts were dried and evaporated to a brown gum which was dissolved in ethanol, filtered to remove salts, and evaporated to a yellow foam. This foam was extracted with refluxing benzene (3 × 200 ml.) for 1½ hr. periods. The residue obtained after evaporation of the benzene was triturated with ether until the insoluble portion had become completely powdery. The ethereal filtrate was evaporated to a yellow gum which was chromatographed in benzene (150 ml.) on neutral alumina (150 g.; activity 3). The column was eluted with benzene (15 × 150 ml.) and with 3 : 1 benzene–ether (20 × 150 ml.). The oil obtained from the benzene–ether fractions was distilled in a short-path still and the fraction of b. p. 162°/0·001 mm. was collected and triturated with pentane to yield pale yellow crystalline pinacol (0·64 g.), m. p. 78—80° (Found: C, 70·6; H, 7·2; N, 5·05. $C_{16}H_{19}NO_3$ requires C, 70·3; H, 7·0; N, 5·1%).

(c) 2-p-*Chloro*-3-3′-*pyridylbutane*-2,3-*diol* (III). The aqueous mixture obtained after distillation of the catholyte was chilled and the aqueous phase decanted from the orange-yellow cake which was then dissolved in methylene chloride (250 ml.). The methylene chloride solution was extracted with N-hydrochloric acid (4 × 300 ml.), and the extracts were made basic with 2N-potassium hydroxide, saturated with sodium chloride, and extracted with methylene chloride (4 × 200 ml.). The methylene chloride solution was dried (Na_2SO_4) and evaporated to a yellow-brown foam.

As there was still present at this stage a small amount of 3-acetylpyridine, the presence of which made isolation of the desired mixed pinacol difficult, it was necessary to remove this ketone by use of a suitable reagent. Therefore, the foam obtained was refluxed and stirred for 1½ hr. in anhydrous ethanol (345 ml.) with anhydrous sodium sulphate (172 g.), Girard's reagent " T " (37·8 g.), and acetic acid (37·8 ml.). The mixture was cooled and poured into water (1625 ml.) containing sodium hydroxide (19 g.) and ice (740 g.). An additional quantity of sodium hydroxide was added if necessary to adjust the solution to pH 8—8·5 and the whole was extracted with methylene chloride. The methylene chloride extracts were combined,

XUM

washed well with water, dried, and evaporated to dryness. The residue was extracted with ether (6 × 250 ml.) until the gum which was formed on contact with ether had changed completely to a powder. The combined extracts were washed well with water, dried, and evaporated to dryness. Distillation in a short-path still at 160°/0·001 mm. gave the *pinacol* (34·0 g.), m. p. 88—90° (Found: C, 64·7; H, 6·0; N, 5·0. $C_{15}H_{16}ClNO_2$ requires C, 64·9; H, 5·8; N, 5·0%).

(d) *2-Phenyl-3-3′-pyridylbutane-2,3-diol* (V). The catholyte was treated as described in the previous isolation procedure. The gummy cake obtained was dissolved in a mixture of 2N-hydrochloric acid (250 ml.) and methylene chloride (250 ml.). After separation, the methylene chloride solution was re-extracted with 2N-hydrochloric acid (3 × 100 ml.). The combined acid extracts were filtered and washed with ether. The solution was made basic with 2N-potassium hydroxide, saturated with sodium chloride, and extracted with methylene chloride. The extracts were dried overnight (Na_2SO_4). The pale yellow precipitate (pinacol from 3-acetylpyridine) was filtered off together with the drying agent. The methylene chloride filtrate was evaporated under reduced pressure to a yellow-amber foam.

The ketonic contaminants were removed by dissolving the foam in anhydrous ethanol (140 ml.) which with stirring was refluxed for 1½ hr. with anhydrous sodium sulphate (85 g.), Girard's reagent " T " (20 g.), and acetic acid (20 ml.). The mixture was chilled and poured into water (800 ml.) containing sodium hydroxide (10 g.), sodium chloride (400 g.), and ice (350 g.). The resulting basic mixture was extracted with methylene chloride, and the extracts were washed with water, dried, and evaporated under reduced pressure. The residue obtained was extracted with ether (6 × 250 ml.), and the extracts were washed with water, dried, and evaporated under reduced pressure. Short-path distillation of the residue gave the *pinacol*, b. p. 130—135°/0·001 mm., which, on cooling, was a white hygroscopic powder (12·5 g.), m. p. 118—120° (Found: C, 73·6; H, 7·15; N, 5·9. $C_{15}H_{17}NO_2$ requires C, 74·0; H, 7·0; N, 5·75%).

5-Chloro-1-methyl-2-3′-pyridylindene (IV).—A solution of undistilled pinacol (III) (70 g.) in concentrated hydrochloric acid (1 l.) was refluxed for 36 hr., filtered, chilled, and kept below 20° while the filtrate was made basic with a saturated sodium hydroxide solution. The supernatant liquid was decanted from the gum and extracted with methylene chloride (3 × 600 ml.). These extracts were used to dissolve the gum, then dried (Na_2SO_4), filtered, and evaporated to dryness under reduced pressure. The residue was exhaustively extracted with ether, and the extracts were combined and evaporated to dryness. The residue on crystallization from anhydrous ethanol gave yellow crystals of the *indene* (18·9 g.), m. p. 99—100° (Found: C, 74·8; H, 5·2; N, 5·7; Cl, 14·6. $C_{15}H_{12}ClN$ requires C, 74·5; H, 5·0; N, 5·8; Cl, 14·7%), $\lambda_{max.}$ 226—227 (ε 5240), 301—306 (ε 11200), 323sh Å (ε 6750).

An additional quantity of indene (10 g.) was obtained by evaporating the ethanol filtrate to dryness and passing the residue in 3 : 1 pentane–benzene (1 l.) through an alumina column (activity 2; 1 kg.). The column was eluted with the pentane–benzene solution (10 × 1 l.). The first 2 fractions were discarded and the subsequent fractions upon evaporation yielded the crystalline indene.

1-Methyl-2-3′-pyridylindene (VI).—The pinacol, 2-phenyl-3-3′-pyridylbutane-2,3-diol (V) (12·5 g.) was refluxed for 48 hr. in concentrated hydrochloric acid (800 ml.). The solution was heated for an additional 15 min. with Norite, filtered, chilled, made basic with sodium hydroxide solution, and extracted a number of times with ether. The dried ether extracts were evaporated to dryness and the residue triturated exhaustively with pentane, which on evaporation followed by short-path distillation (127—132°/0·005 mm.) gave pale yellow solid. Recrystallization from 40% ethanol gave pale yellow crystals of *indene* (4·6 g.), m. p. 59·5—60·5° (Found: C, 86·7; H, 6·3; N, 6·5. $C_{15}H_{13}N$ requires C, 86·9; H, 6·3; N, 6·75%). The *hydrochloride*, made by using dry hydrogen chloride and ether, had m. p. 178·5—180° (Found: C, 73·8; H, 6·0; N, 5·8. $C_{15}H_{14}ClN$ requires C, 73·9; H, 5·8; N, 5·7%).

Undistilled pinacol, of ~95% purity, was also satisfactory for this preparation.

1-Methyl-5-nitro-2-3′-pyridylindene Nitrate (VII).—The undistilled indene (VI) was suitable for this reaction. To the indene (2·95 g.) at 0° was added portionwise, with swirling, concentrated nitric acid (150 ml.). After 2 hr. at 0° the solution was poured with stirring into 2 l. of ice and water and the mixture set aside for ½ hr. The precipitate was collected and recrystallized from 95% ethanol, to yield the yellow *product* (2·16 g.), m. p. 165° (decomp.) (Found: C, 57·4; H, 4·2; N, 13·15. $C_{15}H_{13}N_3O_5$ requires C, 57·1; H, 4·15; N, 13·3%).

5-Amino-1-methyl-2-3′-pyridylindene (VIII).—A mixture of the nitroindene nitrate (VII) (1·93 g.), granular tin (5·8 g.), and 15% hydrochloric acid (570 ml.) was heated with occasional

agitation on a steam-bath for 5 hr. The hot solution was poured into water (500 ml.), heated with Norite, filtered, chilled, made basic with aqueous sodium hydroxide and extracted with ether. Evaporation of the ether gave a semisolid mass which solidified. This was extracted with hot hexane, the hexane extracts being then concentrated and refrigerated, to yield the yellow crystalline *indene* (320 mg.), m. p. 132—134° (Found: C, 81·3; H, 6·5; N, 12·6. $C_{15}H_{14}N_2$ requires C, 81·0; H, 6·3; N, 12·6%).

To a solution of the 5-aminoindene (50 mg.) in concentrated hydrochloric acid (2 ml.) at −5° was added, with stirring during 10 min., a cold solution of sodium nitrite (20 mg.) in water (1 ml.). After an additional 15 minutes' stirring, the diazonium solution was poured into a cold stirred solution of cuprous chloride (30 mg.) in 28% hydrochloric acid (1·5 ml.). After 30 min., the mixture was allowed to warm to room temperature and stirring continued for 3 hr. Finally the stirred mixture was warmed to 70° and the dark red solution then decanted and chilled. The solution was made basic and extracted with ether. The ether extracts were dried and evaporated. The residue was extracted with pentane. Slow evaporation gave crystals, m. p. 98—100°, alone or mixed with 5-chloro-1-methyl-2-3′-pyridylindene. The infrared spectra of the compounds were identical.

RESEARCH DIVISION, CIBA PHARMACEUTICAL PRODUCTS, INC., SUMMIT, NEW JERSEY, U.S.A.
[Present address (M. J. A.): CHEMICAL RESEARCH DEPARTMENT, ELECTRO-OPTICAL SYSTEMS, INC., PASADENA, CALIFORNIA, U.S.A.]

[*Received, October 27th,* 1960.]

---

398. *The Isolation of Festuclavine and Two New Clavine Alkaloids from* Aspergillus fumigatus *Fres.*

By J. F. SPILSBURY and S. WILKINSON.

Festuclavine, previously isolated from saprophytic cultures of strains of ergot (*Claviceps*) found on certain grasses, has been found in cultures of *Aspergillus fumigatus* Fres. Two new alkaloids, also of the clavine type, have been isolated and characterised, and for them the names fumigaclavine A and B are proposed. Fumigaclavine B, which is deacetylfumigaclavine A, has also been found in *Rhizopus arrhizus* Fischer.

IN an investigation on the growth of certain fungi in artificial culture it was decided to examine them for the presence of alkaloids (in the sense of basic materials obtained by solvent-extraction of the basified culture).

As a routine procedure the mycelium was macerated with 2% tartaric acid in 3 : 7 aqueous acetone. After filtration, the acetone was removed under reduced pressure, and the aqueous concentrate was extracted with ether to remove pigments and fats, then made alkaline with aqueous ammonia, and again extracted with ether. Basic material was removed from the ether solution with 0·5N-aqueous hydrochloric acid. These acid extracts were then tested for alkaloids with the usual reagents. Indoles were detected with dimethylaminobenzaldehyde either in a test tube according to the procedure of Allport and Cocking [1] or on filter paper by spraying with Ehrlich's reagent. The results of these tests are summarised in Table 1.

Interest particularly centred around the production of indole alkaloids since these have hitherto only been reported in species of *Claviceps* and in naturally produced *Ustilago zeae*.[2] Whilst the *Phycomyces* gave a barely detectable amount of alkaloid and the *Rhizopus arrhizus* only sufficient subsequently to be identified by paper chromatography as fumigaclavine B, the yield from *Aspergillus fumigatus* (W.R.L. Culture No. CN 1740, originally isolated from a case of mycosis in an osprey) was sufficiently high to suggest that the isolation and characterisation of its alkaloids would be practicable.

[1] Allport and Cocking, *Quart. J. Pharm. Pharmacol.*, 1932, **5**, 341.
[2] Mas, *Bol. Soc. quím. Perú*, 1938, **4**, 3.

TABLE 1. *Alkaloid tests on fungal mycelia.*

Reagents: M = Mayer's; W = Wagner's; D = Dragendorff's; S = Sonnenschein's; STA = silicotungstic acid; E = Ehrlich's.

	Reagents					
	M	W	D	S	STA	E
Phycomycetes						
Absidia corymbifera (Cohn) Sacc.	+	++	++	+	+	—
Absidia ramosa (Lindt) Lendner	+	++	++	+	+	—
Mortierella pusilla Oudem.	+	++	++	+	+	—
Mucor pusillus Lindt	+	+	+	+	+	—
Mucor ramannianus Möller	+	++	++	+	—	—
Phycomyces nitens (Agardh) Kunze	+	++	++	+	+	•
Rhizopus arrhizus Fischer	+	++	+	+	+	•
Rhizopus nigricans Ehrenb.	++	+++	+++	+++	+	•
Syncephelastrum racemosum (Cohn) Schroet.	+	++	++	++	+	—
Ascomycetes						
Claviceps paspali Stev. et Hall	+	+	+	+	+	—
Cordyceps ophioglossoides Link	—	—	+	—	—	—
Martinia panamaensis Whetzel	+	+	+	+	+	•
Basidiomycetes						
Flammulina velutipes (Curr. ex Fr.) Karst.	+	+	+	+	+	—
Gymnopilus junonius (Fr.) Orton	+	+	+	+	+	—
Piptoporus betulinus (Bull.) Karst.	+	+	+	+	+	—
Pleurotus cornucopiae (Paulet ex Pers.) Rolland	+	+	+	+	+	—
Pleurotus lignatilis (Pers. ex Fr.) Kummer	+	+	+	+	+	—
Polyporellus squamosus (Huds.) Karst.	+	+	+	+	+	—
Ustilago perennans Rostr.	+	+	+	+	—	—
Ustilago zeae (Beckm.) Unger	+	+	+	+	—	—
Fungi imperfecti						
Acrostalagmus cinnabarinus Cda.	+	++	++	+	+	—
Aleurisma carnis (Brooks et Hansford) Bisby	—	+	+	+	—	—
Aspergillus fischeri Wehmer	++	++	++	++	++	—
Aspergillus flavus Link	++	++	++	++	+	—
Aspergillus fumigatus Fres.	+++	+++	+++	+++	+++	†
Aspergillus niger van Tiegh.	—	+	+	+	—	—
Aspergillus ochraceus Wilhelm	+	++	++	+	+	—
Aspergillus ruber Bremer	+	++	++	++	++	†
Aspergillus sulphureus (Fres.) Thom et Church	—	+	—	—	—	—
Aspergillus ustus (Bain.) Thom et Church	++	++	++	++	+	—
Aspergillus versicolor (Vuill.) Tiraboschi	++	++	++	++	+	—
Calcarisporium arbuscula Preuss	+	++	++	++	—	—
Colletotrichum atramentarium (B. et Br.) Taub.	++	++	+	+	+	—
Colletotrichum biologicum Chaudhuri	++	++	++	++	+	—
Colletotrichum fuscum Laubert	+	++	++	+	+	—
Colletotrichum solanicolum O'Gara	++	++	++	++	+	—
Coniothyrium concentricum (Desm.) Sacc.	—	+	+	+	—	—
Epicoccum nigrum Link	+	++	++	+	+	—
Gliocladium deliquescens Sopp	+	++	++	+	+	—
Phoma herbarum Westend.	+	+	+	+	—	—
Penicillium avellaneum Thom et Church	+	+	+	+	+	—
Penicillium brefeldianum Dodge	++	++	++	++	++	—
Penicillium lilacinum Thom	+	++	++	+	+	—
Penicillium thomii Maire	+	++	++	++	+	—
Scopulariopsis brevicaulis (Sacc.) Bain.	+	+	++	+	+	—
Sepedonium chrysospermum (Bull.) Fr.	+	++	++	+	—	—
Stemphylium asperulum Sacc.	+	++	++	++	+	—
Trichoderma viride Pers. ex Fr.	+	++	++	+	—	—
Trichophyton schoenleini (Leb.) Lang. et Milochev.	+	++	++	+	—	—
Trichothecium roseum Link ex Fr.	+	++	++	+	+	—

* Pale blue. † Blue.

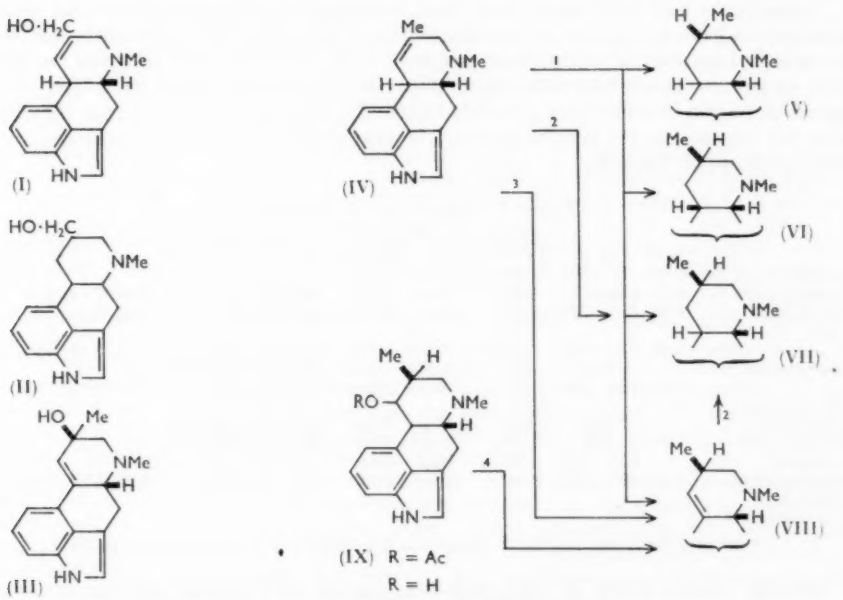
XUM

A malt extract enriched with lactose and asparagine was the medium chosen and the best results were obtained with heavily sporulating cultures as the inoculum; floccose vegetative growth tended to produce lower yields. Preliminary chemical assays of the total alkaloids extracted by chloroform from the cultures, based on the colorimetric estimation of the alkaloids of ergot with dimethylaminobenzaldehyde,[1] showed the alkaloids were present both in the mycelium and in the medium and that maximum production of the order of 150 mg. per l. of total culture was reached after approximately 60 days. The yield was slightly improved by addition of calcium carbonate (0·1%), but addition of tryptophan, apart from stimulating growth in the early stages, had no significant effect. Because of the pathogenicity of the organism, cultures were killed by steaming before extraction, which proved to have an advantage over the use of formaldehyde, as the spores were wetted and their dispersal on harvesting was avoided; also a higher proportion of alkaloid was released into the medium.

It was later found possible to produce the alkaloids in cultures of the fungus grown on sterilised and aerated rye grains. From 1·5 l. of grain 315 mg. of total alkaloids were isolated.

The presence of gliotoxin, a known indole-disulphide metabolite of *A. fumigatus*,[3] could not be demonstrated, but free sulphur was isolated during the extraction.

Paper chromatography was used extensively; the R_F (centre) values quoted, unless



otherwise stated, refer to descending techniques on Whatman No. 1 paper with the solvent system, sodium chloride (8%) in aqueous acetic acid (2%), and a ten-inch distance of travel of the solvent front. Thus, the crude total alkaloids were found to contain a major component, of R_F 0·62 (fumigaclavine A), and two minor components, of R_F 0·51 (fumigaclavine B) and 0·36 (festuclavine) in the approximate proportions 10 : 0·5 : 1 respectively.

[1] Kidd, *Science*, 1947, **105**, 511; Menzel, Wintersteiner, and Hoogerheide, *J. Biol. Chem.*, 1944, **152**, 419.

XUM

A number of yellow, highly fluorescent spots were also found. The three alkaloids were separated by chromatography on alumina washed with acetic acid.

Fumigaclavine A, $C_{18}H_{22}N_2O_2$, gave an intense blue colour with Allport and Cocking's reagent,[1] similar to that given by the alkaloids of ergot, suggesting that the 2-position of the indole nucleus was unsubstituted. An acetyl group was detected and mild alkaline hydrolysis gave deacetylfumigaclavine A, $C_{16}H_{20}N_2O$, identical with fumigaclavine B. Acetylation of fumigaclavine B gave fumigaclavine A, indicating that rearrangement had not occurred during hydrolysis. The easy deacetylation, and strong infrared bands at 1725 and 1241 cm.$^{-1}$ indicated an ester. Fumigaclavine B had one *C*-Me and one *N*-Me group, and the absence of a band at 310 mμ indicated that there was no double bond conjugated with the indole nucleus. Prolonged hydrogenation (Adams catalyst) resulted in the absorption of ~4 mol. of hydrogen.

The sclerotia as well as saprophytic cultures of *Agropyrum*-type ergot fungus parasitic on *Agropyrum semicostatum* Nees, *Trisetum bifidum* Ohwi, *Festuca rubra* L., etc., found growing in Japan, yielded elymoclavine (I), agroclavine (IV), secaclavine [4] (alkaloid X) (II), festuclavine [4] (alkaloid Y) (VII), and, later, pyroclavine (alkaloid Z) (V), costaclavine (alkaloid U) (VI), and isosetoclavine (alkaloid V) (III).[5]

The identity of the festuclavine isolated was proved by analysis and comparison of the physical properties (see Table 2), including ultraviolet and infrared spectra, with those of a sample prepared by hydrogenation of agroclavine.[6,7]

Yamatodani and Abe [8] had shown that reduction of agroclavine (IV) with sodium in butan-1-ol gave, in addition to pyroclavine (V), costaclavine (VI) and festuclavine (VII), an isomer of agroclavine designated lysergine (VIII) which was also obtained, in better yield, by heating agroclavine with sodium butoxide. The change in the ultraviolet spectra (figures not quoted), which now resembled that of lysergic acid, indicated that the double bond had migrated to the position in which it was conjugated with the benzene ring of the indole nucleus (see Table 3).

TABLE 2. *Properties of alkaloids.*

	R_F	M. p.	$[\alpha]_{5461}$ (pyridine)	On paper u.v.	On paper Ehrlich	$\lambda_{max.}$ (mμ)	log ε
Fumigaclavine A	0·62	84—85°	−56·7° *	Blue	Blue		
Fumigaclavine B	0·51	244—245	−113	Blue	Blue	225, 275, 282, 293	4·49, 3·79, 3·82, 3·72
Festuclavine isolated	0·36	238—239	−128	None	Blue	224, 276, 281, —	4·53, 3·81, 3·84, —
,, from agroclavine †	0·36	238—239	−125·3	None	Blue	224, 276, 281, —	4·54, 3·84, 3·86, —
	—	242	−129	None	Blue	225, 275, 282, 292	— — — —
,, from fumigaclavine B	0·36	238—239	−121	None	Blue	224, 276, 281, —	4·54, 3·82, 3·84, —
Pyroclavine	—	204	−105	None	Blue	225, 275, 282, 292	— — — —
Costaclavine [5]	—	182	+59	None	Blue	225, 275, 282, 292	— — — —
Lysergine [5]	—	265—267	+99	Blue	Blue	— — — —	— — — —
Anhydrofumigaclavine B (= lysergine)	0·25	266—267	+98	Blue	Blue	226, 239, 310, —	4·23, 4·20, 3·49, —

* Hydrochloride in MeOH. † Figures in the second row are from refs. 4 and 5.

Heating fumigaclavine B with soda-lime caused dehydration and the ultraviolet spectrum of the product, $C_{16}H_{18}N_2$, showed that a conjugated double bond had been introduced. Further, the physical constants agreed with those recorded for lysergine (see Table 2). Anhydrofumigaclavine B and lysergine are therefore identical. Further proof was obtained, when, as reported by Yamatodani and Abe [8] for lysergine, anhydrofumigaclavine B on catalytic hydrogenation gave festuclavine (VII).

[4] Abe and Yamatodani, *J. Agric. Chem. Soc. Japan*, 1954, **28**, 501.
[5] Abe, Yamatodani, Yamano, and Kusumoto, *Bull. Agric. Chem. Soc. Japan*, 1956, **20**, 59.
[6] Yamatodani and Abe, *Bull. Agric. Chem. Soc. Japan*, 1955, **19**, 94.
[7] Abe, *Ann. Rep. Takeda Res. Lab.*, 1951, **10**, 145.
[8] Yamatodani and Abe, *Bull. Agric. Chem. Soc. Japan*, 1956, **20**, 95.

TABLE 3. *Ultraviolet absorption bands.*

	$\lambda_{max.}$ (mμ)				log ε				Ref.
Agroclavine (IV)	225	—	284	293	3·88	—	3·88	3·81	9
Fumigaclavine B (IX; R = H)	225	275	282	293	4·49	3·79	3·82	3·72	
Anhydrofumigaclavine B (lysergine) (VIII)	226	239	—	310	4·23	4·20	—	3·49	
Setoclavine (isomer of III)	—	243	—	317	—	4·38	—	4·04	*a*
	226	242	—	315	—	—	—	—	5
Lysergic acid (VIII; CO_2H in place of Me)	—	242	—	317	—	—	—	—	*a*

[a] Stoll, Brack, Kobel, Hofmann, and Brunner, *Helv. Chim. Acta*, 1954, **37**, 1815.

The ease of acetylation of fumigaclavine B and the fact that the tertiary hydroxyl group in isosetoclavine (III) is not acetylated,[9] in conjunction with the other evidence described, suggest that the hydroxyl group in fumigaclavine B is secondary and the formulæ for fumigaclavine A and B are therefore (IX; R = Ac and H, respectively).

EXPERIMENTAL

Alumina used for chromatography was supplied by Savory and Moore and deactivated with 10% aqueous acetic acid. Ultraviolet spectra were determined for EtOH solutions with a Hilger Uvispek, and infrared spectra for potassium chloride discs with a Unicam S.P. 100 spectrophotometer.

Growth of the Fungus.—Malt extract was the basic medium used. The most satisfactory one produced was " Kepler " malt extract (10%) enriched with lactose (5%) and asparagine (0·5%). The pH was adjusted to 5·8 and the medium heated in an autoclave for 30 min. at 15 lb./sq. in. Production was carried out in Thomson culture flasks with an average of 250 ml. of medium per flask. Inoculation was carried out with a heavy spore suspension of *A. fumigatus* produced on malt agar and incubated at 23°. Maximum alkaloid concentration was found after 60 days' incubation. The cultures were killed either by the addition of formaldehyde (2%) or by steaming for 1 hr.

Extraction of the Alkaloids.—The mycelium from a total of 2875 flasks of culture was separated in a basket centrifuge, lined with a linen bag, coated with a thin layer of Hyflo supercel to retain the spores. The filtrate was conveniently processed in batches of 75 l. and the mycelium from each such batch extracted separately.

The filtrate (75 l.) was brought to pH 10 with aqueous ammonia (*d* 0·88) and stirred for 6 hr. in a stainless-steel tank with chloroform (75 l.). Some emulsification occurred which slowly dispersed. The aqueous layer was withdrawn and discarded. A second batch of filtrate was introduced, basified, and extracted with the same chloroform solution. After two such extractions the chloroform was replaced with fresh solvent.

The mycelium from 75 l. of culture was macerated with chloroform in a Waring blender and stirred in a stainless-steel tank with chloroform (total, 50 l.) whilst aqueous ammonia (*d* 0·88; 200 ml.) was added. After 6 hr. the mycelium was separated on a centrifuge, returned to the tank, and again stirred with chloroform (50 l.) and aqueous ammonia (200 ml.). This second chloroform extract was used for the next batch of mycelium.

The combined chloroform extracts from the mycelium and filtrate were concentrated under reduced pressure in a circulating-still to a volume of 10 l., then filtered through a thin layer of filter-aid, and the chloroform was removed under reduced pressure. The thick oily residue was dissolved in dry ether (3 l.) and filtered, and a 5% solution of anhydrous oxalic acid in acetone added until precipitation was complete. The oxalate was filtered off, washed with ether, and dried (yield, 55·9 g.). The filtrate slowly deposited sulphur.

A solution of the oxalate (55·9 g.) in water (250 ml.) was filtered, then basified with aqueous ammonia, and the precipitate filtered off, washed with water, and dried (40·2 g.). Extraction of the filtrate with chloroform gave a highly pigmented sticky solid (0·5 g.).

Fractionation of the Alkaloids.—The crude base (20 g.) was passed in chloroform–benzene (1 : 2) down a column of alumina (5 × 25 cm.). The chromatogram was developed with the same solvent mixture and fractions (10 ml.) were collected and examined by paper chromatography, with the following results: 1—10, R_F 0·62 (fumigaclavine A); 11—47 fumigaclavine A + trace R_F 0·51 (fumigaclavine B); 48—76 fumigaclavine B + trace of fumigaclavine A; 80—176 R_F 0·36, festuclavine.

[9] Hofmann, Brunner, Kobel, and Brack, *Helv. Chim. Acta*, 1957, **40**, 1358.

XUM

Fractions 11—47 were evaporated and the residue was dissolved in the same solvent mixture and passed down an alumina column (4 × 15 cm.), giving fractions (10 ml.): 1—16 fumigaclavine A; 16—20 fumigaclavine A + trace of fumigaclavine B; 21—50 fumigaclavine B.

Fractions 48—76 from the first and 16—20 from the second column were evaporated and the combined residues were fractionated as before on alumina (2 × 10 cm.), giving fractions (5 ml.): 1—10 fumigaclavine A; 15—20 fumigaclavine B.

Fumigaclavine A (IX; R = Ac) crystallised from aqueous methanol (charcoal) in colourless needles, m. p. 84—85° (12·4 g.) (Found: C, 72·1; H, 7·1; N, 9·2; Ac, 15·0. $C_{18}H_{22}N_2O_2$ requires C, 72·5; H, 7·4; N, 9·4; Ac, 14·8%). Its *hydrochloride* crystallised from ethanol in prisms, m. p. 304—305° (decomp.) (inserted at 300°), $[\alpha]_{5461}^{22}$ −56·7° (*c* 1·5 in MeOH) (Found: C, 64·3; H, 6·8; N, 8·6; Cl, 10·3; Ac, 12·5; NMe, 9·4; OMe, 0. $C_{18}H_{23}ClN_2O_2$ requires C, 64·6; H, 6·9; N, 8·4; Cl, 10·6; Ac, 12·9; NMe, 8·7%).

The hydrochloride, when crystallised from glacial acetic acid, gave *fumigaclavine A monohydrochloride monoacetate*, m. p. *ca.* 306° (decomp.) (Found: N, 7·4; Cl 9·3; Ac, 19·5. $C_{20}H_{27}ClN_2O_4$ requires N, 7·1; Cl, 9·0; Ac, 21·8%).

The *methiodide* formed hair-like crystals (from methanol), m. p. 266° (decomp.), $[\alpha]_{5461}^{22}$ −23·7° (*c* 0·3 in MeOH) (Found: C, 51·5; H, 5·9; N, 6·6. $C_{19}H_{25}IN_2O_2$ requires C, 51·8; H, 5·7; N, 6·4%).

Fumigaclavine B (IX; R = H). Fractions 21—50 from the second and 11—50 from the third column gave a resin (0·65 g.) which crystallised from aqueous ethanol in needles, m. p. 244—245° (at 260° the melt solidified and then remelted at 265—267°), $[\alpha]_{5461}^{22}$ −6·3° (*c* 1·2 in MeOH), −113° (*c* 0·6 in pyridine) (Found: C, 74·9; H, 7·9; N, 11·1. $C_{16}H_{20}N_2O$ requires C, 75·0; H, 7·9; N, 10·9%). The *methiodide* (from ethanol–ether) had m. p. 309—310° (decomp.) (Found: N, 7·1; I, 31·6. $C_{17}H_{23}IN_2O$ requires N, 7·0; I, 31·9%).

Festuclavine. The residue (0·89 g.) from fractions 80—176 of the first column crystallised from light petroleum (b. p. 60—80°)–ether in colourless needles, m. p. 238—239° (decomp.), and then sublimed at 150—160°/0·01 mm. as prisms, m. p. 238—239° (decomp.), $[\alpha]_{5461}^{22}$ −128° (*c* 0·4 in pyridine) (Found: C, 80·2; H, 8·4; N, 11·4. $C_{16}H_{20}N_2$ requires C, 80·0; H, 8·4; N, 11·7%).

Deacetylfumigaclavine A (*Fumigaclavine* B).—(*a*) Fumigaclavine A hydrochloride (0·1157 g.) was dissolved in a 5% solution (10 ml.) of potassium hydroxide in 80% aqueous ethanol. After 12 hr. $[\alpha]_{5461}^{22}$ had fallen from −80·4° to a steady value −6·9°. Re-acetylation of the product (acetic anhydride and pyridine on the steam-bath for 30 min.) and conversion into the hydrochloride gave fumigaclavine A hydrochloride, m. p. 304—305° (decomp.), $[\alpha]_{5461}^{22}$ −56·2° (*c* 0·5 in MeOH) (Found: C, 64·6; H, 6·8%). Racemisation had therefore not occurred during the alkaline hydrolysis.

(*b*) Fumigaclavine A (1·3 g.) was refluxed in methanolic 2N-potassium hydroxide (25 ml.) for 1 hr. Water (25 ml.) was added, the methanol evaporated under reduced pressure, and the crystalline residue filtered off and washed with water. Recrystallisation from aqueous methanol and then ethanol gave colourless needles, m. p. 244—245°, $[\alpha]_{5461}^{22}$ −113·4° (*c* 0·6 in pyridine), −7·0° (*c* 1 in MeOH) (Found: C, 75·3; H, 7·7; N, 10·6; OMe, 4·4%). The mixed m. p. with fumigaclavine B was not depresed and the R_F values (0·51) were identical. The methiodide crystallised from methanol and ether in prisms, m. p. 310—311° (decomp.) (Found: C, 51·3; H, 5·7; N, 6·9; I, 31·6%).

Anhydrodeacetylfumigaclavine A (*Lysergine*) (VIII).—Fumigaclavine B (0·5 g.) was intimately ground with soda-lime (3 g.), covered with soda-lime (1·5 g.), and heated at 260—270° in a slow stream of nitrogen, the gas evolved being passed through dilute hydrochloric acid. After 5 min. the reactants were sublimed at 150—160°/0·01 mm. Paper chromatography of the sublimate revealed a blue-fluorescent spot (R_F 0·25) (giving a blue colour with Ehrlich's reagent), a little unchanged fumigaclavine B (R_F 0·51), and a number of minor pigmented highly fluorescent spots. The solid was triturated with cold chloroform (2·5 ml.), and the residue, recrystallised from ethanol, sublimed at 160—165°/0·01 mm.; this gave prisms, m. p. 266—267°, $[\alpha]_{5461}^{23}$ +98° (*c* 1 in pyridine) (Found: C, 80·5; H, 7·6; N, 11·7. Calc. for $C_{16}H_{18}N_2$: C, 80·7; H, 7·6; N, 11·8%). The methiodide had m. p. 253—254° (from methanol and ether) (Found: C, 53·3; H, 5·9; N, 7·2. Calc. for $C_{17}H_{21}IN_2$: C, 53·7; H, 5·5; N, 7·4%). The contents of the acid trap were evaporated and the small amount of residue identified as methylamine hydrochloride by paper chromatography (Whatman No. 1 paper; butanol–acetic acid–water, 4 : 1 : 5).

Festuclavine (VII).—(a) *From agroclavine.* Agroclavine (0·476 g.) was hydrogenated in

glacial acetic acid (20 ml.) at atmospheric pressure over platinum oxide (0·1 g.) until 1 mol. of hydrogen (44 ml.) had been taken up. On Whatman No. 1 paper, with the usual solvent and a run of 17 cm., the following spots were detected (colours refer to those in ultraviolet light and with Ehrlich's reagent, respectively): R_F 0·40, trace of agroclavine (none, blue); R_F 0·43, major component (none, blue); R_F 0·65, trace (blue, blue). The catalyst was filtered off and the acetic acid evaporated under reduced pressure (nitrogen leak). The residue was dissolved in 1 : 2 chloroform–benzene and fractionated on alumina (2 × 15 cm.). Fractions (5 ml.) 1—10 contained pigment and the material of R_F 0·65 (0·09 g.). Fractions 15—25 gave only festuclavine, R_F 0·43 (0·15 g.), which crystallised from ethanol and then sublimed as prisms, m. p. 238—239°, $[\alpha]_{5461}^{22}$ −125·3° (*c* 0·6 in pyridine).

(b) *From anhydrodeacetylfumigaclavine A* (*lysergine*) (VIII).—Lysergine (0·1 g.) was hydrogenated in glacial acetic acid (10 ml.) over platinum oxide (0·1 g.) at atmospheric pressure until 1 mol. of hydrogen had been taken up. The catalyst was filtered off and the acetic acid evaporated under reduced pressure. The residue was passed in 1 : 2 chloroform–benzene through alumina (1 × 10 cm.). After the initial passage of a narrow blue-fluorescent band pure fractions of a component of R_F 0·43 were obtained. These were combined, evaporated, and sublimed at 150—155°/0·01 mm. to give prisms, m. p. 238—239°, $[\alpha]_{5461}^{22}$ −121° (*c* 0·38 in pyridine). The mixed m. p.s of the three samples of festuclavine were undepressed and the R_F values (0·41) were identical.

The authors thank Miss D. M. Land and Mr. R. Lovegrove for technical assistance, Dr. A. J. Everett for the measurements of the spectra, and Mr. P. R. W. Baker for the microanalyses.

WELLCOME RESEARCH LABORATORIES, LANGLEY COURT, BECKENHAM, KENT.

[*Received, November 11th,* 1960.]

---

399. *Modified Steroid Hormones. Part XXI.** 17β-*Hydroxy*-11-*methylene and* -11β-*methyl*-5α-*androstan*-3-*one.*

By D. N. KIRK and V. PETROW.

The 11-oxo-group in certain 5α-steroids is found to react with methyl- and ethyl-magnesium halides, giving 11β-hydroxy-11α-alkyl derivatives.

11-Oxotigogenin acetate has been converted into 11β-hydroxy-11α-methyltigogenin acetate and thence by dehydration with thionyl chloride–pyridine or with formic acid into 9,11-dehydro-11-methyl- or 11-methylene-tigogenin acetate. The last compound has been transformed by standard methods into 17β-hydroxy-11-methylene- and -11β-methyl-androstan-3-one.

SOME years ago we observed the ready reaction of certain 11-oxo-steroids with methylmagnesium halide to give the corresponding 11-hydroxy-11-methyl derivatives. Extension of these observations was not feasible at the time, but has since become possible. In the meantime other laboratories have reported the smooth reaction of 11-oxo-steroids with methyl-lithium [1] and have commented on the unsatisfactory nature of the corresponding condensation employing the Grignard reagent.

Our initial experiments were directed to the reaction of methylmagnesium halide with such compounds as 3,3:17,17-bisethylenedioxyandrost-5-en-11-one, but no appreciable reaction could be observed. No better results attended the use of 5β-pregnan-11-one derivatives. We finally turned to 11-oxotigogenin acetate,[2] which was of interest at the time as a potential raw material for cortisone production. Treatment of this compound

* Part XX, *J.*, 1960, 4664.

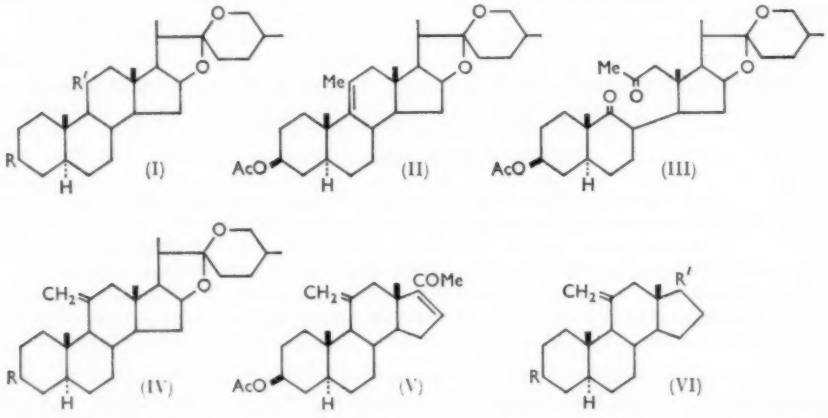
[1] Ringold, Batres, and Zderic, *Tetrahedron*, 1958, **2**, 164; Fonken and Hogg, *ibid.*, p. 365; Fonken, Hogg, and McIntosh, *J. Org. Chem.*, 1959, **24**, 1600; Beyler, Hoffman, and Sarett, *J. Amer. Chem. Soc.*, 1960, **82**, 178; Zderic, Batres, Limón, Cartio, Lisci, Monroy, Necoechea, and Ringold, *ibid.*, p. 3404; Elks, *J.*, 1960, 3333 (published after submission of the present manuscript).

[2] Cornforth, Osbond, and Phillipps, *J.*, 1954, 907; Schmidlin and Wettstein, *Helv. Chim. Acta* 1953, **36**, 1241.

(I; R = –OAc, ··H; R′ = O) with the methyl-Grignard reagent in refluxing ether–benzene gave 11α-methyl-5α,25D-spirostan-3β,11β-diol (I; R = –OH, ··H; R′ = –OH, ··Me) in excellent yield. The last compound was converted into a diol monoacetate and passed into a hydroxy-ketone on oxidation with chromic acid. The hydroxy-ketone was separately obtained from 11-oxotigogenone [3] (I; R = R′ = O) by conversion into the 3,3-dimethoxy-derivative, reaction with methylmagnesium iodide, and regeneration of the 3-oxo-group. It is accordingly formulated as 11β-hydroxy-11α-methyltigogenone (I; R = O; R′ = –OH, ··Me).

Dehydration of 3β-acetoxy-11α-methyl-5α,25D-spirostan-11β-ol with thionyl chloride–pyridine furnished 3β-acetoxy-11-methyl-5α,25D-spirost-9(11)-ene (II), which was converted by osmic acid into 3β-acetoxy-11β-methyl-5α,25D-spirostan-9α,11α-diol. This diol was unaffected by acetic anhydride–pyridine, but was smoothly cleaved by periodic acid to a diketone assigned the constitution of 3β-acetoxy-11-methyl-9,11-seco-5α,25D-spirostan-9,11-dione (III). The infrared spectrum of the last compound showed a shoulder at 1348 cm.$^{-1}$; this is tentatively assigned to the methyl ketone moiety [4] as it was no longer present in the spectrum of the reduction product of the 9,11-dione (III) with sodium borohydride.

Dehydration of 3β-acetoxy-11α-methyl-5α,25D-spirostan-11β-ol with formic acid at 25—50° gave 11-methylenetigogenin acetate (IV; R = –OAc, ··H) which crystallised directly from the solution in excellent yield. On hydroxylation with osmic acid this product (IV) gave 11ξ-hydroxy-11ξ-hydroxymethyl derivative (one acetylatable hydroxyl



group) which was cleaved to 11-oxotigogenin acetate by periodic acid. The 11-methylene derivative (IV; R = –OAc, ··H) was also prepared by dehydration of the 11β-hydroxy-11α-methyl derivative (I; R = –OAc, ··H, R′ = –OH, ··Me) with acetic anhydride–acetic acid–toluene-*p*-sulphonic acid or by direct isomerisation of the 9(11)-ene (II) with formic acid at room temperature.

On catalytic hydrogenation 11-methylenetigogenin acetate (IV; R = –OAc, ··H) absorbed 1 mol. of hydrogen. The product no longer showed the infrared absorption band at 1636 cm.$^{-1}$ characteristic of the exocyclic methylene group and is regarded as 11β-methyltigogenin acetate.

Reaction of 11-oxotigogenin acetate with ethylmagnesium iodide gave the corresponding 11α-ethyl-11β-hydroxy-derivative. Dehydration with thionyl chloride–pyridine or with formic acid then led to the formation of the same product, tentatively regarded as

[3] Djerassi, Ringold, and Rosenkranz, *J. Amer. Chem. Soc.*, 1951, **73**, 5513.
[4] Jones and Cole, *J. Amer. Chem. Soc.*, 1952, **74**, 5648; Jones, Cole, and Nolin, *ibid.*, p. 5662.

XUM

11-ethylidenetigogenin (acetate) on the basis of physical data (see p. 2095). 3β,20β-Diacetoxy-5α-pregnan-11-one [5] was similarly converted into 11α-methyl-5α-pregnane-3β,11β,20β-triol and thence, by way of the diacetate, into both the 11-methyl-9(11)-ene and the 11-methylene derivative.

Degradation of the side chain of 11-methylenetigogenin acetate with acetic anhydride, pyridine, and methylamine hydrochloride [6] furnished 3β,26-diacetoxy-11-methylene-5α-furost-20(22)-ene, which was converted by oxidation with hydrogen peroxide, followed by refluxing with acetic acid, into 3β-acetoxy-11-methylene-5α-pregn-16-en-20-one (V). The constitution of this product was established by catalytic hydrogenation to 3β-acetoxy-11-methylene-5α-pregnan-20-one, followed by reduction of the carbonyl group with sodium borohydride and acetylation, which afforded 3β,20β-diacetoxy-11-methylene-5α-pregnane identical with material prepared *via* the Grignard reaction on 3β,20β-diacetoxy-5α-pregnan-11-one (above).

3β-Acetoxy-11-methylene-5α-pregn-16-en-20-one (V) was converted by Beckmann rearrangement of its oxime into 3β-acetoxy-11-methylene-5α-androstan-17-one (VI; R = −OAc, ··H; R′ = O), and thence into the 3,17-dione (VI; R = R′ = O). Selective protection of the 3-oxo-group in the last compound by conversion into the 3,3-dimethoxy-derivative, followed by reduction of the 17-oxo-group and regeneration of the carbonyl function at $C_{(3)}$, furnished 17β-hydroxy-11-methyleneandrostan-3-one (VI; R = O; R′ = −OH, ··H), which was required for study as an anabolic agent. Catalytic hydrogenation of the propionate of the last compound followed by oxidation of the newly formed 3-hydroxyl group, gave the corresponding 17β-hydroxy-11β-methylandrostan-3-one (as propionate).

Experimental

Rotations were measured in a 1 dm. tube for chloroform solutions. Ultraviolet absorption spectra were kindly determined by Mr. M. T. Davies, B.Sc., and Miss D. F. Dobson, B.Sc.

11α-*Methyl*-5α,25D-*spirostan*-3β,11β-*diol* (I; R = −OH, ··H; R′ = −OH, ··Me).—11-Oxotigogenin acetate (I; R = −OAc, ··H; R′ = O) (100 g.) in benzene (2 l.) was added to a solution of methylmagnesium iodide prepared from magnesium (100 g.), methyl iodide (260 ml.), and ether (2 l.). The mixture was heated under reflux for 3 hr., cooled, and poured into ammonium chloride solution containing ice. The organic layer was separated and washed, and the solvents were removed under reduced pressure. A portion of the residual gum, purified from acetone–hexane, gave 11α-methyl-5α,25D-spirostan-3β,11β-diol in prisms, m. p. 209—212°, $[\alpha]_D^{23}$ −58° (*c* 0·93) (Found: C, 75·5; H, 10·2. Calc. for $C_{28}H_{46}O_4$: C, 75·3; H, 10·4%).

The main part of the product above was treated on the steam-bath with pyridine (300 ml.) and acetic anhydride (200 ml.) for ½ hr., then poured into water. The precipitated solids were collected after 2 hr., dried, and purified from acetone, followed by ethyl acetate, to give 3β-acetoxy-11α-methyl-5α,25D-spirostan-11β-ol in prisms, m. p. 193—195°, $[\alpha]_D^{23}$ −63° (*c* 0·88) (Found: C, 73·4; H, 10·0. Calc. for $C_{30}H_{48}O_5$: C, 73·7; H, 9·9%).

Similar procedures employing ethylmagnesium iodide led to 11α-*ethyl*-5α,25D-*spirostan*-3β,11β-*diol*, prisms (from methanol), m. p. 215—218°, $[\alpha]_D^{24}$ −34° (*c* 0·79) (Found: C, 75·7; H, 10·0. $C_{29}H_{48}O_4$ requires C, 75·6; H, 10·5%), and its 3-*acetate*, needles (from methylene chloride–methanol), m. p. 177—179°, $[\alpha]_D^{25}$ −39·5 (*c* 0·87) (Found: C, 74·0; H, 9·8. $C_{31}H_{50}O_5$ requires C, 74·05; H, 10·0%).

11β-*Hydroxy*-11α-*methyl*-5α,25D-*spirostan*-3-*one* (I; R = O; R′ = −OH, ··Me).—(*a*) 11α-Methyl-5α,25D-spirostan-3β,11β-diol (4 g.) in anhydrous pyridine (40 ml.) was treated with the complex prepared from chromium trioxide (4 g.) in pyridine (40 ml.).[8] After 5 hours' stirring the mixture was left overnight, then diluted with benzene and filtered. The filtrate was washed, dried (Na_2SO_4), decolorised (charcoal), and evaporated. Purification from ethanol gave 11β-*hydroxy*-11α-*methyl*-5α,25D-*spirostan*-3-*one* in blades, m. p. 210—213°, $[\alpha]_D^{27}$ −52°

[5] Callow and James, *J.*, 1956, 4744.
[6] B.P. 749,697/1956.
[7] Rosenkranz, Mancera, Sondheimer, and Djerassi, *J. Org. Chem.*, 1956, **21**, 520.
[8] Poos, Arth, Beyler, and Sarett, *J. Amer. Chem. Soc.*, 1953, **75**, 422.

XUM

(*c* 0·41), $\nu_{max.}$ (in CS_2) 1718 cm.$^{-1}$ (3-ketone) (Found: C, 75·4; H, 9·3. $C_{28}H_{44}O_4$ requires C, 75·6; H, 10·0%).

(*b*) 5α,25D-Spirostan-3,11-dione (I; R = R′ = O) (20 g.) and oxalic acid (1 g.) in anhydrous methanol (800 ml.) were heated under reflux for 2 hr., then cooled, and the crystalline product was purified from methanol–methylene chloride containing a drop of pyridine. The resulting 3,3-*dimethoxy*-5α,25D-*spirostan*-11-*one* formed prisms, m. p. 192—195° (with evolution of gas), $[\alpha]_D^{23}$ −23° (*c* 1·30), $\nu_{max.}$ (in CCl_4) 1709 cm.$^{-1}$, (in CS_2) 1182, 1103 cm.$^{-1}$ (3,3-dimethoxy) (Found: C, 73·1; H, 9·6. $C_{29}H_{46}O_5$ requires C, 73·4; H, 9·8%).

The ketal was submitted to the Grignard reaction with methylmagnesium iodide. The infrared spectrum of the crude product showed almost complete loss of the 11-carbonyl band, and of the dimethoxy-system, which had apparently been converted into a 2-methoxy-Δ^2-system (bands at 1690 and 1172 cm.$^{-1}$). The total product was dissolved in warm acetic acid (250 ml.), diluted with water (25 ml.), and after ½ hr. poured into water. The precipitated solids were purified from ethanol, to give 11β-hydroxy-11α-methyl-5α,25D-spirostan-3-one identical with the sample prepared as under (*a*).

3β-*Acetoxy*-11-*methyl*-5α,25D-*spirost*-9(11)-*ene* (II).—3β-Acetoxy-11α-methyl-5α,25D-spirostan-11β-ol (10 g.) in anhydrous pyridine (100 ml.) at −20° was treated with thionyl chloride (5 ml.) and the mixture allowed to warm to room temperature during ½ hr. Precipitation into water gave a light brown solid which was dried at 30—40°, dissolved in boiling hexane, and decolorised with charcoal. The solution was concentrated, and on cooling gave 3β-acetoxy-11-methyl-5α,25D-spirost-9(11)-ene. Purification from hexane or from methanol gave material of variable m. p., between 110° and 126°, but careful chromatography on alumina gave no evidence of heterogeneity. The product formed needles, $[\alpha]_D^{25}$ −13° (*c* 0·84), $\nu_{max.}$ (in CS_2) 1735 cm.$^{-1}$ (OAc) (Found: C, 76·3; H, 9·7. Calc. for $C_{30}H_{46}O_4$: C, 76·55; H, 9·85%).

Saponification of the foregoing 3-acetate (1 g.) with potassium hydroxide (0·5 g.) in 80% methanol (100 ml.) gave the 3β-*hydroxy-compound*, which separated from methanol in solvated plates, m. p. 120—130°, transformed by drying at 105° *in vacuo* into an amorphous powder, m. p. 191—194°, $[\alpha]_D^{23}$ −18° (*c* 0·57) (Found: C, 78·2; H, 10·1. $C_{28}H_{44}O_3$ requires C, 78·45; H, 10·35%).

Hydroxylation of the 9(11)-*ene* (II) *with Osmic Acid.*—3β-Acetoxy-11-methyl-5α,25D-spirost-9(11)-ene (4·1 g.) in pyridine (160 ml.) was treated with osmic acid for 5 days. The solution was saturated with hydrogen sulphide, diluted with benzene, and filtered. The filtrate was washed with dilute acid and water, dried (Na_2SO_4), and evaporated. The solid residue, purified from acetone followed by ethyl acetate, gave 3β-*acetoxy*-11β-*methyl*-5α,25D-*spirostan*-9α,11α-*diol* in needles, m. p. 231—233°, $[\alpha]_D^{20}$ −58° (*c* 0·62), $\nu_{max.}$ (in CS_2) 3595, 3535 (*cis*-diol), and 1738 cm.$^{-1}$ (OAc) (Found: C, 70·9; H, 9·8. $C_{30}H_{48}O_6$ requires C, 71·4; H, 9·6%).

Cleavage of the 9α,11α-*Diol with Periodic Acid.*—The foregoing 9α,11α-diol (2·3 g.) in dioxan (150 ml.) was treated with periodic acid (2·5 g.) in water (25 ml.) for 3 days at room temperature. The solution was poured into water, and the solid product purified from aqueous methanol to give 3β-*acetoxy*-11-*methyl*-9,11-*seco*-5α,25D-*spirostan*-9,11-*dione* (III) in prisms, m. p. 104—106°, $[\alpha]_D^{22}$ −100° (*c* 0·43), $\nu_{max.}$ (in CCl_4) 1734 (OAc), 1719, 1705 (ketones), 1431 (·CO·CH_2·), and 1348 cm.$^{-1}$ (−COMe) [Found: (after drying at 90° *in vacuo*): C, 71·5; H, 9·0. $C_{30}H_{46}O_6$ requires C, 71·7; H, 9·2%]. This gave a *mono-oxime*, m. p. 179—183° (needles from aqueous methanol) (Found: C, 69·6; H, 9·15; N, 2·9. $C_{30}H_{47}NO_6$ requires C, 69·6; H, 9·15; N, 2·7%).

Saponification of a sample of this material in methanolic hydrochloric acid (0·5%) for 24 hr. gave an amorphous product, $\nu_{max.}$ (in CCl_4) 3613 (OH), 1720, 1707 (ketones), 1431 (CO·CH_2), and 1347·5 cm.$^{-1}$ (−COMe).

Reduction of the 9,11-*Diketone.*—The 9,11-dione (30 mg.) in methanol (6 ml.) was treated with sodium borohydride (50 mg.) and sodium hydroxide (50 mg.) in water (1 ml.) for 6 hr. at room temperature. The solution was diluted with water, and the product extracted with ether. The resulting amorphous 3β,9ξ,11ξ-triol showed no infrared absorption bands near 1348 cm.$^{-1}$.

3β-*Acetoxy*-11-*methylene*-5α,25D-*spirostan* (IV; R = −OAc, ··H).—(*a*) 3β-Acetoxy-11α-methyl-5α,25D-spirostan-11β-ol (20 g.) was dissolved in 98—100% formic acid (400 ml.) at 40°. On cooling, a crystalline product separated, which was collected after 3 hr., washed with methanol, and purified from ethanol, to give 3β-acetoxy-11-methylene-5α,25D-spirostan in needles, m. p. 186—188°, $[\alpha]_D^{21}$ −60° (*c* 0·52), $\nu_{max.}$ (in CCl_4) 3100 (:CH_2), 1737 (OAc), and 1636 cm.$^{-1}$ (:CH_2) [9] (Found: C, 76·6; H, 10·0. Calc. for $C_{30}H_{46}O_4$: C, 76·55; H, 9·85%).

[9] Cf. Sondheimer and Mechoulam, *J. Amer. Chem. Soc.*, 1957, **79**, 5029.

(*b*) 3β-Acetoxy-11-methyl-5α,25D-spirost-9(11)-ene (250 mg.) was stirred with formic acid (10 ml.) for 5 hr., then poured into water. Purification from ethanol gave 3β-acetoxy-11-methylene-5α,25D-spirostan, m. p. 185—187°, not depressed in admixture with the sample prepared as under (*a*).

(*c*) 3β-Acetoxy-11α-methyl-5α,25D-spirostan-11β-ol (0·55 g.) in acetic acid (25 ml.) and acetic anhydride (10 ml.) containing toluene-*p*-sulphonic acid (50 mg.) was left overnight at room temperature. The product was again the 11-methylene compound.

Saponification of the foregoing 3-acetoxy-11-methylene compound (0·6 g.) with potassium hydroxide (400 mg.) in 90% methanol (80 ml.) gave 11-*methylenetigogenin* (IV; R = ⁻OH, ··H), fibrous crystals (from methanol), m. p. 204—207°, $[\alpha]_D^{24}$ −54° (*c* 0·28), $\nu_{max.}$ (in CCl_4) 3610 (OH), 1644 cm.$^{-1}$ (:CH_2) (Found: C, 78·2; H, 10·2. $C_{28}H_{44}O_3$ requires C, 78·45; H, 10·35%).

Dehydration of the 11α-ethyl-11β-hydroxy-compound (I; R = ⁻OAc, ··H; R′ = ⁻OH, ··Et) by any of the above procedures gave what is believed to be 3β-*acetoxy*-11-*ethylidene*-5α,25D-*spirostan* which separated from ethanol in needles, m. p. 193—195°, $[\alpha]_D^{19}$ −53° (*c* 0·53), $\nu_{max.}$ (in CCl_4) 1739 cm.$^{-1}$ (Found: C, 76·5; H, 9·7. $C_{31}H_{48}O_4$ requires C, 76·8; H, 10·0%).

11-*Methylene*-5α,25D-*spirostan*-3-*one* (IV; R = O).—The foregoing 3β-hydroxy-compound (5 g.) in acetone (150 ml.) was treated dropwise with the chromic acid reagent [chromium trioxide (240 g.), sulphuric acid (230 ml.), water to 1 l.] until the presence of excess of oxidant was indicated by the colour of the mixture. The solution was diluted with water to 1 l., and the precipitated solid purified from acetone to give 11-*methylene*-5α,25D-*spirostan*-3-*one* in blades, m. p. 208—212°, $[\alpha]_D^{23}$ −42° (*c* 0·46), $\nu_{max.}$ (in CCl_4) 3105, 1636 (:CH_2), and 1717 cm.$^{-1}$ (C=O) (Found: C, 78·8; H, 9·7. $C_{28}H_{42}O_3$ requires C, 78·8; H, 9·9%).

An attempt to crystallise the 3-ketone from methanol converted it into the 3,3-*dimethoxy-derivative*, m. p. 188—190°, $[\alpha]_D^{23}$ −58° (*c* 0·29), $\nu_{max.}$ (in CCl_4) 3107, 1635 (:CH_2) (no carbonyl absorption) (Found: C, 76·4; H, 9·95. $C_{30}H_{48}O_4$ requires C, 76·2; H, 10·2%).

Hydroxylation of 3β-*Acetoxy*-11-*methylene*-5α,25D-*spirostan* (IV; R = ⁻OAc, ··H).—A solution of the 11-methylene compound (4 g.) and osmic acid (2·4 g.) in pyridine (100 ml.) was kept at room temperature for 12 days, then saturated with hydrogen sulphide, diluted with benzene, and filtered. The filtrate was washed with dilute hydrochloric acid and water, and the solvent was removed. The resulting yellow-green solid was decolorised by passage in ether solution through a column of alumina (10 g.) and crystallised from acetone, to give 3β-acetoxy-11-hydroxymethyl-5α,25D-spirostan-11-ol in flakes, m. p. 238—239°, $[\alpha]_D$ −61° (*c* 0·37). Satisfactory analytical results could not be obtained, as the product appeared to be tenaciously solvated [Found: (after drying at 60° *in vacuo*) C, 68·0; H, 9·7; (after drying at 120° *in vacuo*) C, 69·7; H, 9·5. $C_{30}H_{48}O_6$ requires C, 71·4; H, 9·6. $C_{30}H_{48}O_6,H_2O$ requires C, 68·9; H, 9·6%].

Acetylation with acetic anhydride and pyridine (1 : 1) for ½ hr. on the steam-bath gave the 11-*acetoxymethyl*-11-*hydroxy-derivative* which separated from methanol in needles, m. p. 162—163°, $[\alpha]_D^{20}$ −65° (*c* 0·63), $\nu_{max.}$ (in CS_2) 3569, 3490 (associated OH), and 1729 cm.$^{-1}$ (associated OAc) (Found: C, 70·0; H, 8·9. $C_{32}H_{50}O_7$ requires C, 70·3; H, 9·2%).

Cleavage of the 11-hydroxy-11-hydroxymethyl derivative by periodic acid as described for the 9α,11α-diol (above) gave 11-oxotigogenin acetate, identified by mixed m. p. and infrared comparison with an authentic sample.

3β-*Acetoxy*-11β-*methyl*-5α,25D-*spirostan*.—The 11-methylene compound (IV; R = ⁻OAc, ··H) (1 g.) in acetic acid (50 ml.) was hydrogenated over Adams platinum catalyst (100 mg.). After filtration the solvent was evaporated under reduced pressure. Purification of the residue from ethanol gave 3β-acetoxy-11β-methyl-5α,25D-spirostan as needles, m. p. 199—200°, $[\alpha]_D^{21}$ −63° (*c* 1·00), $\nu_{max.}$ (in CCl_4) 1735 cm.$^{-1}$ (Found: C, 75·9; H, 10·2. Calc. for $C_{30}H_{48}O_4$: C, 76·2; H, 10·2%).

11α-*Methyl*-5α-*pregnane*-3β,11β,20β-*triol*.—3β,20β-Diacetoxy-5α-pregnan-11-one (1·8 g.) in benzene (30 ml.) was added to the Grignard reagent prepared from magnesium (2 g.) and methyl iodide (5·5 ml.) in ether (50 ml.). The mixture was heated under reflux for 3 hr., cooled, and poured into aqueous ammonium chloride. The product was extracted with chloroform and purified from aqueous methanol, to give 11α-*methyl*-5α-*pregnane*-3β,11β,20β-*triol* as a powder, m. p. 197—199°, $[\alpha]_D^{23}$ +20° (*c* 0·49) (Found: C, 75·6; H, 10·8. $C_{22}H_{38}O_3$ requires C, 75·4; H, 10·9%).

The 3,20-*diacetate*, prepared by heating the foregoing triol (1 g.) with acetic anhydride (2 ml.) and pyridine (4 ml.) for 4 hr. on the steam-bath, separated from aqueous methanol in

prisms, m. p. 224—227°, $[\alpha]_D^{23}$ +16° (*c* 0·38) (Found: C, 72·2; H, 9·6. $C_{26}H_{42}O_5$ requires C, 71·85; H, 9·7%).

11β-*Hydroxy*-11α-*methyl*-5α-*pregnane*-3,20-*dione*.—The foregoing 3β,11β,20β-triol (1·4 g.) in anhydrous pyridine (16 ml.) was oxidised with the complex prepared from chromium trioxide (2 g.) in pyridine (20 ml.) for 2 days at room temperature. The mixture was diluted with ethyl acetate and filtered, and the filtrate washed with water, dilute sulphuric acid, and water until neutral. After removal of the solvent the residue was purified from acetone–hexane to give 11β-*hydroxy*-11α-*methyl*-5α-*pregnane*-3,20-*dione* in prisms, m. p. 224—226°, $[\alpha]_D^{22}$ +96° (*c* 0·35), $\nu_{max.}$ (in $CHCl_3$) 3603 (OH), and 1702 cm.$^{-1}$ (ketones) (Found: C, 76·3; H, 10·1. $C_{22}H_{34}O_3$ requires C, 76·3; H, 9·9%).

3β,20β-*Diacetoxy*-11-*methyl*-5α-*pregn*-9(11)-*ene*.—A solution of 3β,20β-diacetoxy-11α-methyl-5α-pregnan-11β-ol (2·03 g.) in anhydrous pyridine (50 ml.) was cooled to −20° and treated with thionyl chloride (2 ml.). The mixture was allowed to warm to room temperature during 10 min., then poured into dilute sulphuric acid. Extraction with ether and crystallisation from aqueous methanol gave the 11-*methyl*-9(11)-*ene* in rods, m. p. 126—128°, $[\alpha]_D^{23}$ +88° (*c* 0·34), $\nu_{max.}$ (in CS_2) 1734 cm.$^{-1}$ (acetates) (Found: C, 74·75; H, 9·6. $C_{26}H_{40}O_4$ requires C, 74·95; H, 9·7%).

3β,20β-*Diacetoxy*-11-*methylene*-5α-*pregnane*.—(a) 3β,20β-Diacetoxy-11α-methyl-5α-pregnan-11β-ol (200 mg.) in formic acid (10 ml.) was warmed to 40°, then allowed to cool and set aside for 3 hr. It was poured into water. Extraction with benzene and purification from aqueous methanol gave the 11-*methylene derivative* in leaflets, m. p. 148—150°, $[\alpha]_D^{25}$ +19° (*c* 0·62), $\nu_{max.}$ (in CCl_4) 3095, 1632 (:CH_2), 1729 cm.$^{-1}$ (OAc) (Found: C, 74·85; H, 9·9. $C_{26}H_{40}O_4$ requires C, 74·95; H, 9·7%).

(b) *From* 3β,20β-*diacetoxy*-11-*methyl*-5α-*pregn*-9(11)-*ene*. The 9(11)-ene (100 mg.) in formic acid (2 ml.) was heated on the steam-bath for 20 min. The product, isolated as under (a), proved to be the 11-methylene derivative.

(c) *From* 3β-*acetoxy*-11-*methylene*-5α-*pregn*-16-*en*-20-*one* (V) (see below). Hydrogenation of the 16-en-20-one (0·5 g.) in methanol (100 ml.) over 2% palladium–barium carbonate (50 mg.) led to the uptake of one mol. of hydrogen. The catalyst was removed, and the solution concentrated until crystallisation commenced. Purification from methanol gave 3β-*acetoxy*-11-*methylene*-5α-*pregnan*-20-*one* in prismatic needles, m. p. 137—138°, $[\alpha]_D^{28}$ +85° (*c* 0·32) (Found: C, 77·0; H, 9·7. $C_{24}H_{36}O_3$ requires C, 77·4; H, 9·7%).

This 20-one (350 mg.) in 90% methanol (25 ml.) was treated with sodium hydroxide (300 mg.) and sodium borohydride (150 mg.) under reflux for 2 hr., and the solution was then concentrated to small bulk and cooled. The separated solids were purified from aqueous methanol and from acetone, to give 11-*methylene*-5α-*pregnane*-3β,20β-*diol* in needles, m. p. 203—206°, $[\alpha]_D^{29}$ +54° (*c* 0·21), $\nu_{max.}$ (in Nujol) 3580, 3247 (OH), 1632, 895 cm.$^{-1}$ (:CH_2) (Found: C, 79·2; H, 10·6. $C_{22}H_{36}O_2$ requires C, 79·5; H, 10·9%).

The diol (100 mg.) with acetic anhydride (1 ml.) and pyridine (1 ml.) on the steam-bath for 2 hr. gave 3β,20β-diacetoxy-11-methylene-5α-pregnane, identical with the samples prepared as under (a) and (b) above.

Degradation of the Spiro-ketal System in 11-*Methylenetigogenin Acetate* (IV; R = ⁻OAc, ··H).—A mixture of 11-methylenetigogenin acetate (40 g.), pyridine (40 ml.), acetic anhydride (80 ml.), and methylamine hydrochloride (13·4 g.) was heated under reflux for 2·5 hr., cooled, and poured into ice-water. The precipitated product solidified slowly. A sample, crystallised from methanol, gave 3β,26-*diacetoxy*-11-*methylene*-5α-*furost*-20(22)-*ene* in needles, m. p. 94—96°, $[\alpha]_D^{23}$ +30° (*c* 0·61) (Found: C, 75·0; H, 9·3. $C_{32}H_{48}O_5$ requires C, 74·9; H, 9·4%).

The main part of the crude furostene was dissolved in acetic acid (800 ml.) and treated with 30% hydrogen peroxide (350 ml.) for 6 hr. at room temperature. Chloroform (300 ml.) was added, and the mixture was diluted with water. The chloroform was separated, the aqueous phase was re-extracted with chloroform, and the combined extracts were washed and evaporated. A solution of the residue in acetic acid (200 ml.) was heated under reflux for 2 hr., concentrated under reduced pressure, and poured into water. Extraction with chloroform gave a product which, from methanol, gave 3β-*acetoxy*-11-*methylene*-5α-*pregn*-16-*en*-20-*one* in needles, m. p. 184—186°, $[\alpha]_D^{23}$ +34° (*c* 0·42), $\lambda_{max.}$ 238 mμ (ε 8130 in EtOH), $\nu_{max.}$ (in CH_2Cl_2) 1724 (OAc) 1663, 1587 (Δ^{16}-20-one), and 1636 cm.$^{-1}$ (:CH_2) (Found: C, 77·4; H, 9·5. $C_{24}H_{34}O_3$ requires C, 77·8; H, 9·25%).

The yield of this product was substantially improved by passing the non-crystalline residues,

in benzene solution, through a column of chromatographic alumina (5 g. per 1 g. of residue), evaporating the benzene, and purifying the product from methanol.

The foregoing compound (10 g.) in ethanol (50 ml.) and pyridine (10 ml.) was treated with hydroxylamine hydrochloride (3·5 g.) under reflux for ½ hr. Water (5 ml.) was added, and the solution was cooled to 0°. The crystalline product was purified from ethanol–chloroform, to give the 20-*oxime* as prisms, m. p. 205—210°, $[\alpha]_D^{23}$ +17° (*c* 0·11), $\lambda_{max.}$ 237 mμ (ε 14,660 in EtOH), $\nu_{max.}$ (in CH_2Cl_2) 1719, 1632, and 1584 cm.$^{-1}$ (Found: N, 3·8. $C_{24}H_{35}NO_3$ requires N, 3·6%).

Beckmann Degradation of the Oxime.—A solution of the oxime (8 g.) in anhydrous pyridine (40 ml.), cooled to −10°, was treated dropwise with phosphorus oxychloride (16 ml.) in pyridine (48 ml.). The mixture was kept at 0° for 3 hr., then poured on ice (120 g.) and concentrated hydrochloric acid (120 ml.) with stirring, the temperature of the mixture being kept below 50°. The product was a paste which hardened on cooling. It was purified from 80% methanol to give 3β-*acetoxy*-11-*methylene*-5α-*androstan*-17-*one* in needles, m. p. 166—167°, $[\alpha]_D^{23}$ +77° (*c* 0·26), $\nu_{max.}$ (in CCl_4) 3110 and 1638 (:CH_2), 1740, 1735sh (17-ketone and OAc), and 1409 cm.$^{-1}$ (17-ketone) (Found: C, 76·4; H, 9·0. $C_{22}H_{32}O_3$ requires C, 76·7; H, 9·3%).

3β-*Hydroxy*-11-*methylene*-5α-*androstan*-17-*one* (VI; R = −OH, ··H; R′ = O).—Saponification of the foregoing 3-acetate (4·5 g.) with potassium hydroxide (2 g.) in 80% aqueous methanol (50 ml.) under reflux for ½ hr. and purification from aqueous methanol gave 3β-*hydroxy*-11-*methylene*-5α-*androstan*-17-*one* in rhombic plates, m. p. 166—167°, $[\alpha]_D^{24}$ +89° (*c* 0·69), $\nu_{max.}$ (in CCl_4) 3588 (OH), 3115, 1636 (:CH_2), 1742 (17-ketone), (in CS_2) 905 cm.$^{-1}$ (:CH_2) (Found: C, 79·3; H, 10·7. $C_{20}H_{30}O_2$ requires C, 79·4; H, 10·0%).

11-*Methylene*-5α-*androstane*-3β,17β-*diol* (VI; R = R′ = −OH, ··H).—Reduction of the 17-ketone (VI; R = −OH, ··H; R′ = O) (2 g.) with sodium borohydride (400 mg.) in 80% aqueous methanol (40 ml.) for 1 hr. at room temperature, and purification from acetone–hexane gave the 3β,17β-*diol* in prisms, m. p. 192—194°, $[\alpha]_D^{22}$ +20° (*c* 0·19) (Found: C, 78·4; H, 10·6. $C_{20}H_{32}O_2$ requires C, 78·9; H, 10·6%).

11-*Methylene*-5α-*androstane*-3,17-*dione* (VI; R = R′ = O).—3β-Hydroxy-11-methylene-5α-androstan-17-one (8 g.) in " AnalaR " acetone (100 ml.) was treated dropwise with chromic acid reagent (see above) until the presence of excess of oxidant was indicated by the colour of the solution. Water (700 ml.) containing sodium dithionite (0·5 g.) was added, and the acetone was removed under reduced pressure. The precipitated solids were washed free from chromium salts and purified from aqueous acetone, to give the 3,17-*dione* in square plates, m. p. 193—196°, $[\alpha]_D^{22}$ +115° (*c* 0·73), $\nu_{max.}$ (in CCl_4) 3108 and 1637 (:CH_2), 1741 (17-ketone), and 1719 (3-ketone), (in CS_2) 905 cm.$^{-1}$ (:CH_2) (Found: C, 79·75; H, 9·3. $C_{20}H_{28}O_2$ requires C, 79·95; H, 9·4%).

3,3-*Dimethoxy*-11-*methylene*-5α-*androstan*-17-*one* [VI; R = $(MeO)_2$; R′ = O].—The foregoing dione (6 g.) was stirred in anhydrous methanol (120 ml.) and treated with acetyl chloride (0·5 ml.). The precipitate was collected after ½ hr. and purified from ethanol containing 0·5% of pyridine, to give the 3,3-*dimethoxy-derivative* as needles, m. p. 175—178° (decomp.), $[\alpha]_D^{23}$ +138° (*c* 0·13), $\nu_{max.}$ (in CCl_4) 3109, 1640 (:CH_2), 1745 cm.$^{-1}$ (17-ketone) (Found: C, 76·1; H, 9·8. $C_{22}H_{34}O_3$ requires C, 76·3; H, 9·9%).

3,3-*Dimethoxy*-11-*methylene*-5α-*androstan*-17β-*ol* [VI; R = $(MeO)_2$; R′ = −OH, ··H)].—Reduction of the last compound (4·6 g.) in suspension in methanol (120 ml.) with sodium borohydride (1 g.) and sodium hydroxide (1 g.) in water (15 ml.) for 1·5 hr. at room temperature gave a solution which was diluted with water (300 ml.). The precipitate solids were purified from aqueous methanol, to give the 17β-*alcohol* as blades, m. p. 166—167°, $[\alpha]_D^{26}$ +37° (*c* 0·85), $\nu_{max.}$ (in CCl_4) 3616 (OH), 3110, 1636 (:CH_2), (in CS_2) 899 cm.$^{-1}$ (:CH_2) (Found: C, 76·0; H, 10·3. $C_{22}H_{36}O_3$ requires C, 75·8; H, 10·4%).

The 17-*propionate*, prepared by treating the foregoing compound (1·5 g.) with propionic anhydride (3 ml.) in pyridine (10 ml.) for 20 min. on the steam-bath, separated from methanol in flakes, m. p. 145—148°, $[\alpha]_D^{26}$ +6° (*c* 0·69) (Found: C, 74·5; H, 9·9. $C_{25}H_{40}O_4$ requires C, 74·2; H, 10·0%).

17β-*Hydroxy*-11-*methylene*-5α-*androstan*-3-*one* (VI; R = O; R′ = −OH, ··H).—3,3-Dimethoxy-11-methylene-5α-androstan-17β-ol (1 g.) in 70% acetic acid (20 ml.) was heated to 80° for 20 min. The product was poured into water and the precipitate purified from aqueous methanol, to give 17β-*hydroxy*-11-*methylene*-5α-*androstan*-3-*one* in fibrous crystals, m. p. 207—210°, $[\alpha]_D^{26}$ +33° (*c* 0·78), $\nu_{max.}$ (in CCl_4) 3614 (OH), 3102, 1636 (:CH_2), and 1715 (3-ketone),

XUM

(in CS_2) 901 cm.$^{-1}$ (:CH_2) (Found: C, 79·1; H, 9·8. $C_{20}H_{30}O_2$ requires C, 79·4; H, 10·0%). The 17-*acetate* separated from aqueous methanol in plates, m. p. 150—151°, $[\alpha]_D^{23}$ +3° (*c* 0·28) (Found: C, 76·6; H, 9·6. $C_{22}H_{32}O_3$ requires C, 76·7; H, 9·4%). The 17-*propionate* separated from methanol in flakes, m. p. 169—170°, $[\alpha]_D^{23}$ +18° (*c* 0·48) (Found: C, 77·5; H, 9·7. $C_{23}H_{34}O_3$ requires C, 77·05; H, 9·6%).

11β-*Methyl*-17β-*propionyloxy*-5α-*androstan*-3-*one*.—The foregoing propionate (0·8 g.) was hydrogenated in acetic acid (25 ml.) over Adams platinum catalyst (0·1 g.). The uptake of hydrogen ceased after absorption of about 2 mols., indicating reduction of both the methylene and the 3-keto-group. After removal of the catalyst, and of the solvent under reduced pressure, the residue was treated in acetone (30 ml.) with a slight excess of chromic acid reagent (see above). The solution was diluted with water (100 ml.), and the acetone removed under reduced pressure. The precipitated solid, purified from aqueous methanol, gave the *androstanolone propionate* in prisms, m. p. 136—138°, $[\alpha]_D^{24}$ +26° (*c* 0·34), $\nu_{max.}$ (in CCl_4) 1733 (propionate) and 1717 cm.$^{-1}$ (3-ketone).

CHEMICAL RESEARCH LABORATORIES, THE BRITISH DRUG HOUSES LTD.,
LONDON, N.1. [*Received, September 15th*, 1960.]

---

400. *Heterocyclic Derivatives of Guanidine. Part II.*[1] *Some Derived Products.*

By J. E. BANFIELD.

Cyclisation of 2-(α-cyano-α-ethoxycarbonylmethylene)-5-oxo-3,4-diphenyl-3-pyrroline (I) gave ethyl 3-amino-4-(α-ethoxycarbonylbenzylidene)-1,4-dihydro-1-imino-2-naphthoate (II) with ethyl 3,5-dihydro-5-imino-2-oxo-1-phenyl-2*H*-benz[*e*]indole-4-carboxylate (III) as a by-product. Some derivatives of these products are described.

In an analogous reaction, 2,5-di-(α-cyano-α-ethoxycarbonylmethylene)-3,4-diphenyl-3-pyrroline (VIII) gave diethyl 7,9-dihydro-5,9-di-imino-5*H*-dibenzo[*c*,*g*]carbazole-6,8-dicarboxylate (IX).

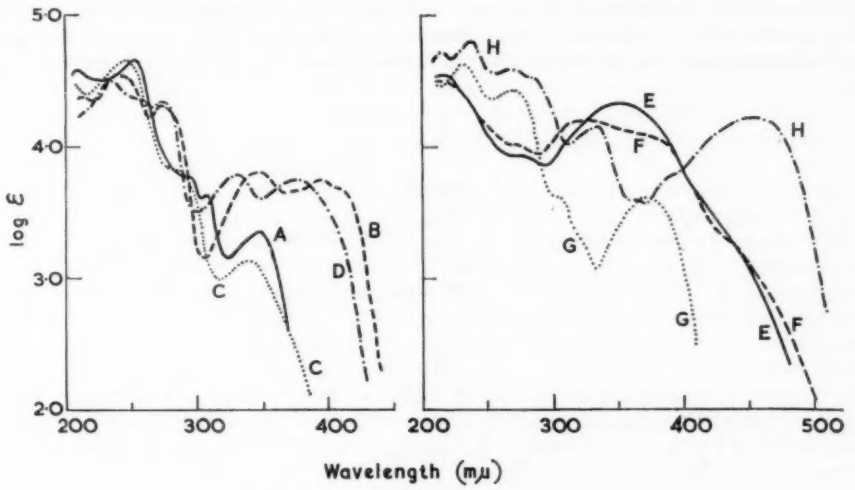
REACTION of ethyl cyanoacetate with 5-guanidino-2-imino-3,4-diphenyl-2*H*-pyrrole and with 2-imino-3,4-diphenyl-5-oxo-3-pyrroline, the latter readily obtained from the former compound, readily provides compounds (VIII) and (I) respectively.[1] The reported cyclisation of *trans*-αβ-dicyanostilbene in sulphuric acid to 3-cyano-2-phenylinden-1-one [2] (an imino-group being lost by hydrolysis) led to the suggestion that the esters (I) and (VIII) might be cyclised similarly.

Reaction of the ester (I) with sulphuric acid gave, unexpectedly, a low yield of a compound of constitution corresponding to the addition of ethanol (which was not lost on sublimation and was presumably provided by a disproportionation); higher yields were obtained when ethanol was isothermally distilled into the reaction mixture. This compound lacked absorption at *ca.* 2200 cm.$^{-1}$. Its ultraviolet absorption (Fig. 1B), being bathochromically and hypochromically displaced from that of the precursor (I), is consistent rather with a cyclic than with an imino-ether structure. It contained two ethoxyl groups (although slightly low ethoxyl values were obtained consistently), both of which were lost on saponification. The genesis of the second ester group can be ascribed to ethanolysis of the lactam group of (I), amides being readily hydrolysed by a unimolecular mechanism under similar conditions.[3] Thus the product is the quinone-imine (II), a structure which is consistent with the spectral change on reductive acetylation (Fig. 1B ⟶ A). The ultraviolet absorption of the reductive acetylation product was of naphthalenic type, although at rather longer wavelengths than usual. However, ethyl

[1] Part I, *J.*, 1960, 2108.
[2] Coe, Gale, Linstead, and Timmons, *J.*, 1957, 123.
[3] Duffy and Leisten, *J.*, 1960, 856.

1,3-diamino-2-naphthoate, known as a product of an analogous cyclisation of ethyl α-cyano-β-imino-γ-phenylbutyrate, is bright yellow.[4] In our hands this base readily yielded a monoacetyl derivative, formulated as ethyl 3-acetamido-1-amino-2-naphthoate, in acetic anhydride at moderate temperatures. This derivative was pale yellow and its ultraviolet absorption (Fig. 1D) resembled somewhat that of the amine (II), although this resemblance is considered fortuitous; it is noteworthy that the colour of 2-hydroxyacetophenone has been ascribed to chelation.[5] This monoacetyl derivative was further acetylated by keten, to give a triacetyl derivative; *C*-acylation being considered unlikely and a band at 870 cm.$^{-1}$ being present (possibly pentasubstituted aromatic), the latter is formulated as ethyl 3-acetamido-1-diacetylamino-2-naphthoate, 2·6 mol. of acid being obtained in an

FIG. 1. FIG. 2.



FIGS. 1—2. *Ultraviolet absorption spectra.*

A, *Compound* (IV; R = H); max. at 348, 308, 296, 253, 215 mμ (log ε 3·359, 3·635, 3·768, 4·663, 4·546). B, *Compound* (II); max. 394, 347, 274, 240 mμ (log ε 3·756, 3·808, 4·324, 4·553). C, *Ethyl 3-acetamido-1-diacetylamino-2-naphthoate*; max. 338, 286, 247 mμ (log ε 3·140, 3·838, 4·662). D, *Ethyl 3-acetamido-1-amino-2-naphthoate*; max. 377, 331, 273, 234 mμ (log ε 3·750, 3·788, 4·348, 4·513). E, *Compound* (III); max. 350, 273, 216 mμ (log ε 4·335, 3·940, 4·541). F, *Compound* (V); max. 327, 272, 214 mμ (log ε 4·205, 4·019, 4·501). G, *Compound* (VII); max. 372, 270, 232 mμ (log ε 3·614, 4·440, 4·623). H, *Compound* (IX); max. 447, 362, 334, 285, 268, 237, 214 mμ (log ε 4·215, 3·600, 4·163, 4·515, 4·593, 4·804, 4·723).

N-acetyl determination. Although having strong ν(NH) absorption in the infrared region, this compound had no active hydrogen in the Zerewitinoff determination (MgMeI in anisole at 95°). Its ultraviolet absorption (Fig. 1C) closely resembled that of the reductive acetylation product of (II) which is formulated (see below) as (IV).

Although the amine (II) decomposed extensively at 230°, and it was recovered from refluxing diphenyl ether, a trace of sodium in this solvent converted it into the lactam (III), which was also obtained as a minor product of the cyclisation of the nitrile (I). Hot acetic acid converted both the amine (II) and the imino-lactam (III) into the oxo-lactam (V) and both this and the amine (II) were hydrolysed by ethanolic sodium hydroxide to the acid (VI). The ultraviolet absorption of the keto-lactam (VI) (Fig. 2F) and the imino-compound (III) (Fig. 2E) differed but in detail and were generally similar to that of both

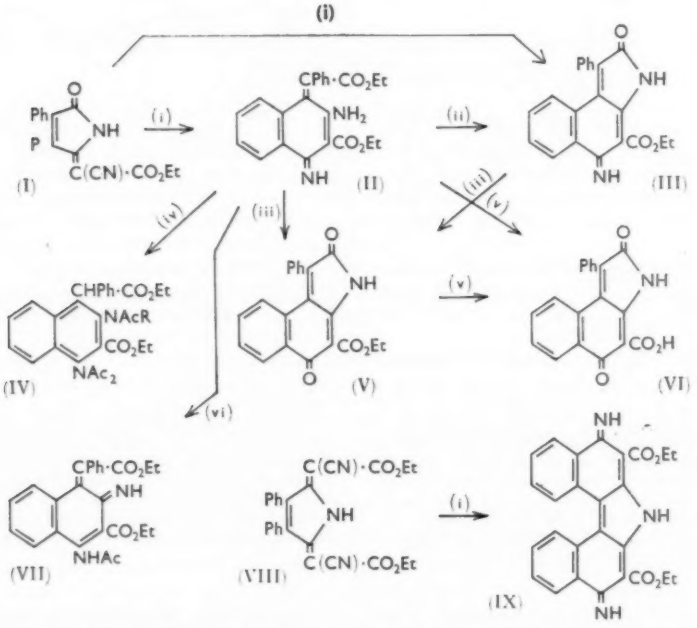
[4] Atkinson and Thorpe, *J.*, 1906, **89**, 1920.
[5] Crawford and Supanekar, *J.*, 1960, 1985.

XUM

the acid (VI) and, to a smaller extent, the ester (II). The absorption of the imino-compound (III) in ethanol was changed by either acetic or perchloric acid and it then somewhat resembled that of the amine (II) the absorption of which was only slightly altered by acid. The amine (II) with keten gave an acetyl derivative the elementary composition of which was more consistent with that of a monoacetyl than a diacetyl derivative, an *N*-acetyl determination giving *ca.* 1 mol. of acid; the *o*-quinone imine structure (VII) is preferred on spectral grounds—mainly the absence of $\nu(NH_2)$ symmetrical and asymmetrical bands at *ca.* 3400 and 3500 cm.$^{-1}$, and its ultraviolet absorption (Fig. 2G).

The bis-ester (VIII) was cyclised by sulphuric acid to its isomer (IX) the structure of which follows from its lack of C:N absorption and from the position of its ultraviolet absorption (Fig. 2H) relative to that of the parent compound (VIII); however, a tautomeric amino-structure also merits consideration for this compound.

The infrared absorption of the above compounds displayed some unexpected features. It is apparent that a doublet at 1680—1693 cm.$^{-1}$ of the ester (VIII) and a band at 1665 cm.$^{-1}$ of compound (IX) are due to αβ-unsaturated ester modes, the latter frequency being



(i) H_2SO_4. (ii) Na–Ph_2O. (iii) AcOH. (iv) Ac_2O–Zn. (v) KOH–EtOH. (vi) CH_2:CO.

lowered by hydrogen bonding. Data for CO·NH in a five-membered unsaturated ring of the above type are not abundant; however, by analogy with δ-lactams (1665 cm.$^{-1}$) and unsaturated δ-lactams (1675 cm.$^{-1}$),[6] this group might be expected to absorb at somewhat higher frequencies than γ-lactams (1700 cm.$^{-1}$);[6] a band at 1749 cm.$^{-1}$ has previously[1] been attributed to such a function in 5-*NN*-dimethylguanidino-2-oxo-3,4-diphenyl-2*H*-pyrrole nitrite. Thus the 1749 cm.$^{-1}$ band of the nitrile (I) can be ascribed to a ν(CO·NH) mode and hence the 1708 cm.$^{-1}$ band to the unsaturated ester function.

[6] R. N. Jones and Sandorfy, in Weissberger, " Techniques of Organic Chemistry, Vol. IX. Chemical Applications of Spectroscopy," Interscience, Publ. Inc., New York, 1956, pp. 458—535.

XUM

For diphenylmaleinimide the doublet at 1764 and 1711 cm.$^{-1}$ is apparently due to this mode, the average frequency (1738 cm.$^{-1}$) possibly being raised somewhat by coupling due to dipole interaction; and for 2-imino-3,4-diphenyl-5-oxo-3-pyrroline, bands at 1729 and 1706 cm.$^{-1}$ are probably (CO·NH) modes split by interaction with the C=NH function. Accordingly strong bands at 1722, 1732, and 1735 cm.$^{-1}$ of compounds (III), (V), and (VI), respectively, are readily recognisable as due to this function, other bands in this region being displaced appropriately as the other functional groups are altered.

For ethyl 3-acetamido-1-amino-2-naphthoate the assignments 3488 [$\nu(NH_2)$ asym.], 3370 [$\nu(NH_2)$ sym.], 3220, 3138 [ν(NH)], 1657 (aromatic ester, bonded), 1631 (NHAc),[7,8] 1610 [$\delta(NH_2)$],[9] and 1553 cm.$^{-1}$ (Amide II) [7] seem reasonable, and for ethyl 3-acetamido-1-diacetylamino-2-naphthoate, absorption at 3348 [ν(NH)], 1680 [ν(NHAc)],[8] 1601 (aromatic C=C), and 1522 cm.$^{-1}$ (Amide II) is in accord with expectation. Data for aromatic secondary amides have been reviewed; [10] two or three bands, depending upon the resolution, appear in the 1690—1730 cm.$^{-1}$ region. Thus *NN*-diacetylaniline absorbs at 1724, 1712, and 1701 cm.$^{-1}$; *NN*-diacetyl-*o*-anisidine at 1728, 1720, and 1704 cm.$^{-1}$; and *NN*-diacetyl-1-naphthylamine at 1727 and 1706 cm.$^{-1}$. Thus it is likely that the secondary amide bands of the triacetyl derivative contribute to the broad and asymmetrical peak at 1710 cm.$^{-1}$ with a shoulder at 1721 cm.$^{-1}$ and an inflection at 1703 cm.$^{-1}$ which must also include the peak expected for the CO_2Et group.

Analyses for the reductive acetylation product from compound (II) indicated a tetra-acetyl or, slightly more probably, a triacetyl derivative, and the compound gave 2—3 mol. of acid in the usual *N*-acetyl determination; but, in view of the low values for some of the above compounds, this is not considered to exclude definitely the tetra-acetyl formulation; results of the active hydrogen determination might be accounted for by the active ethyl diarylacetate hydrogen. Although both ethyl 3-acetamido-1-diacetylamino-2-naphthoate and compound (IV) had somewhat similar absorption in the 1570—1630 cm.$^{-1}$ region, and both absorbed strongly between 1690 and 1740 cm.$^{-1}$, the peaks of this product in the latter range were at quite different positions from those of the simpler analogue; this suggested the alternative formulation of it as the tetra-acetyl compound (IV; R = Ac) which would explain not only the above differences, but also the lack of specific absorption in the NH region, and the lack of a band in the 1500—1650 cm.$^{-1}$ region of a strength expected for an Amide II band; in this case the peak at 1705 cm.$^{-1}$ could be assigned to the secondary amide functions and the peak at 1730 cm.$^{-1}$ to these together with absorption of the unbonded ring ester function. The strong peak at 1786 cm.$^{-1}$ of this compound must be due to the aliphatic CO_2Et group, its frequency being extraordinarily high.

The acetyl derivative (VII) absorbed at 1750 cm.$^{-1}$, again an exceptionally high frequency for, in this case, an αβ-unsaturated ester; absorptions at 3384, 3210 [ν(NH)], 1713 (CO_2Et, aromatic), 1687 (NHAc), 1661 cm.$^{-1}$ (C=N), and 1529 cm.$^{-1}$ (broad) (Amide II) account for the absorption expected in this region for the other functions. There is, in fact, a far closer resemblance between the infrared absorption of ethyl 3-acetamido-1-diacetylamino-2-naphthoate and the acetyl derivative (VII), than between the former and the reductive acetylation product (IV), further raising the possibility that the product (VIII) was in fact a diacetyl derivative. In an attempt to clarify this point this acetyl compound was refluxed in acetic acid in the expectation that cyclisation with loss of ethanol would occur should the β-amino-function not be protected, as in the reaction of compound (II) with this reagent; in the event the acetyl compound was recovered, and its analysis was then unambiguous for the monoacetyl derivative of compound (II). Failure under these conditions to hydrolyse an α-imino-function, or to cyclise the lactam ring at

[7] Gerrard, Lappert, Pyszora, and Wallis, *J.*, 1960, 2144, where mention is made of large shifts of amide I and II bands (complementary) with intermolecular association.
[8] Katritzky and Jones, *J.*, 1959, 2067.
[9] Katritzky and Jones, *J.*, 1959, 3674.
[10] Abramovitch, *J.*, 1957, 1414; see also Cramer and Baer, *Chem. Ber.*, 1960, **93**, 1231.

XUM

the β-nitrogen atom, of this compound seems inconsistent either with an α-acetimido-β-amino-structure or a β-acetamido-α-imino-structure and thus the α-acetamido-β-imino-structure (VII) is further supported. Further, an attempt to hydrolyse the acetyl compound under conditions comparable to those of the *N*-acetyl determination, in which the evolution of (probably) ammonia was noted, gave an acidic product clearly different from the acid (VI). This result seems inexplicable unless hydrolysis of the β-imino-group of compound (VII) to a keto-group is faster than that of the α-acetamido-group. Owing to difficulties in the purification of this saponification product no satisfactory analytical evidence in support of this rationalisation is presented; the structure of this acidic product is, in any case, largely incidental to the above argument.

Prolonged acetylation of compound (II) by keten gave a benzene solvate of the diacetyl derivative which must be formulated as the α-diacetylamino-compound as it was hydrolysed by acetic acid to the monoacetyl compound (VII), secondary amides being known to hydrolyse under these conditions. Although the formation of diacylamines is known to be assisted by the presence of groups adjacent to the amino-function, their formation by the action of keten on aromatic amines is apparently without precedent; neither α- nor β-naphthylamine gave the diacyl derivative under comparable conditions.

The amine (II) has negligible absorption above 1730 cm.$^{-1}$ in the C=O region, and thus the two strong peaks at 1717 and 1677 cm.$^{-1}$ must be due to the two ester functions, both of which may be strongly bonded to adjacent NH or NH_2 groups with consequent reduction in frequency, as in methyl *N*-methylanthranilate,[11] and in the above-mentioned ethyl acetamido-1-amino-2-naphthoate [ν(C=O) not above 1673 cm.$^{-1}$].

Absorption is characteristically strong for the exocyclic C=C function as in compounds (VIII), (I), (II), and (VII); in most of the other compounds it is weak. Frequencies and some further empirical assignments of bands for some of the above compounds are given in the following list.

Spectra.—Frequencies (cm.$^{-1}$) and estimates of the intensities of the main absorption bands for Nujol mulls were estimated from spectra kindly determined by Dr. D. L. Ford, Timbrol Company, Sydney, whom we thank. A Perkin-Elmer model 21 double-beam spectrophotometer fitted with a rock-salt prism was used. Bands in the region of the main Nujol bands, unless very prominent, have been ignored.

Compound (VIII): 3294 (NH); 3034sh,m (arom. CH); 2225m (CN); 1693, 1680 (αβ-unsat. ester, split); 1610s, 1599s (C=C, exocyclic, split), 1563sh,m; 1274s (COCO, ester), 1204s, 1185s, 1165s, 1157, 1110, 1080s, 1070m, 1047s, 1032m, 1013sh, 1004s, 999sh,m, 940, 930, 856s, 775s, 752s, 725s, 700s, 690m.

Compound (IX): 3460m, 3396m, 3330m, (NH); 1665s (αβ-unsat. ester, bonded); 1604s (C=C, C=N); 1551m, 1520m (aromatic); 1316s (CO·CO, ester), 1274, 1250m, 1223s, 1178s, 1171s, 1143m, 1098m, 1085m, 1080m, 1034m, 1019sh, 943, 933, 789m, 756s, 743s, 699s.

Compound (I): 3360s (NH); 2239 (CN), 1749s, 1708asym,s; 1611s, 1600s (C=C, exocyclic, split), 1347m; 1260s (CO·CO, ester), 1176sh,s, 1160s, 1095m, 1089m, 1085m, 1060s, 1003, 968m, 853, 799, 783s, 767m, 761m; 699s [δ(CH), Ph].

Diphenylmaleinimide: 3157s, 3040s, 2722 (NH···O=C), 1764m, 1711s, 1600m, 1342s,asym., 1183, 1146m, 1080, 1072, 1033, 1021s, 950, 929, 848, 809, 775s, 757s, 742m, 708s, 689s.

2-Imino-3,4-diphenyl-5-oxo-3-pyrroline: 3306br, with absorption to 3000, 2744br,m (NH···O=C), 1729s, 1706s, 1661s, 1601m, 1416m, 1362s, 1207m, 1121m, 1071m, 1046m, 1025m, 861m, 856m, 834s, 797s, 767s, 754sh,m, 723s, 701s, 690s.

Ethyl 3-amino-4-(α-ethoxycarbonylbenzylidene)-1,4-dihydro-1-imino-2-naphthoate: 3445s, 3330s (NH_2, NH, bonded); 1717s, 1677s, (CO_2Et); 1614s [δ(NH_2), C=C]; 1603s, 1547, 1515 (arom.), 1437, 1390, 1325, 1310m; 1271s, 1246s (CO·CO, ester), 1227sh, 1175m, 1153m, 1134, 1108, 1084, 1078m, 1066m, 1047, 1021, 1008, 978, 889, 798m; 763s (*o*-disubst. arom.); 699s (Ph).

Compound (III): 3304m, with broad absorption to 2700 (NH and bonded NH); 1722s (CO·NH); 1687s (CO_2Et, bonded), 1672sh; 1612m, 1591m, 1572m (C=C, C=N); 1410, 1345,

[11] Bellamy, "The Infra-red Spectra of Complex Molecules," Methuen, London, 1958, p. 185.

1330, 1274, 1249, 1199, 1174, 1151, 1122, 1096, 1061, 1032, 1002, 977, 922, 802; 769m (*o*-disubst. arom.), 719; 708 (Ph).

Compound (V): 3380m (NH); 1732s, 1720sh (CO·NH, CO_2Et); 1670br,s, 1657sh (C=O); 1622m (C=C); 1599, 1568 (arom.), 1293m, 1272sh, 1230m, 1167, 1142, 1058, 1037, 969, 897; 774 (*o*-disubst. arom.), 739, 723; 705m (Ph–), 693.

Compound (VI): 3370m (NH); 2650br (OH, bonded); 1735s (CO·NH); 1709s,br (CO_2H); 1632s (C=O bonded to OH);[a] 1610m, 1594m, 1580m, 1557m, 1545sh (C=C, arom.); 1405s (CO_2H), 1364s, 1335, 1301s, 1208, 1151m, 1141sh, 1095, 1075, 1058, 1033, 1000, 961m, 897s, 884sh, 843, 818, 800m; 779s (*o*-disubst. arom.), 763, 750, 712m; 705s (Ph), 693m.

Compound (VII): 3384m, 3210m, 1750s, 1713s, 1687s, 1678sh, 1661s; 1629s (C=C), 1602, 1575m, 1529m,br, 1503m, 1400sh, 1334m, 1313m; 1284, 1266m, 1236s (CO·CO, ester), 1219sh, 1175s, 1158s, 1138m, 1124m, 1094s, 1073m, 1050, 1031, 1003, 974, 918, 887, 856, 834, 798, 765s; 748s (*o*-disubst. arom.), 729, 719; 698s (Ph).

Compound (IV): low-intensity broad absorption only in NH region; 1786s, 1730s, 1705s, 1677 infl., 1623; 1595, 1570, 1511 (arom.), 1420sh, 1317s, 1284m; 1237s, 1215sh (CO·CO, ester), 1195, 1185, 1160m, 1145, 1118, 1100, 1079, 1045, 1029, 1022, 1007, 973m, 950, 922, 896, 864, 818; 768s (*o*-disubst. arom.), 729m, 722; 696m (Ph).

Ethyl 3-acetamido-1-diacetylamino-2-naphthoate: 3348, 1721sh, 1710s, 1680m, 1658sh, 1630; 1601m, 1573 (arom.), 1522s, 1489m, 1341, 1331, 1309m, 1288m; 1264s (CO·CO, ester), 1231s, 1200sh, 1168, 1153m, 1142, 1119, 1093m, 1077, 1027, 1017m, 983m, 965sh, 909, 897; 870m (pentasubst. arom.), 860, 792s; 762s (*o*-disubst. arom.), 747sh, 719, 675.

Ethyl 3-acetamido-1-amino-2-naphthoate: 3488s, 3370s, 3220m, 3138s, 2700, 1673sh,m, 1657s, 1631s, 1610m, 1561m, 1553s, 1533m, 1502, 1437; 1345s (CO·CO, ester), 1302, 1276 1247m, 1232s, 1169s, 1143m, 1135sh, 1107, 1087s, 1019, 943, 896; 861m (pentasubst. arom.) 837m, 802s, 776sh; 771m (*o*-disubst. arom.), 743s, 724

[a] Cf. 1-hydroxyanthraquinones; ref. 6, p. 492.

Experimental

Ultraviolet absorption spectra were determined for 95% EtOH solutions on an Unicam S.P. 500 spectrophotometer by Mrs. J. E. Banfield, B.Sc. Identity of compounds which decomposed heavily on melting was in each case confirmed by the identity of their ultraviolet absorption (in addition to elementary analysis), mixed m. p. determination being of little value for compounds of this type.

Cyclisation of 2-(*α-Cyano-α-ethoxycarbonylmethylene*)-5-*oxo*-3,4-*diphenyl*-3-*pyrroline*.—(*a*) In a preliminary experiment the ester (I) (1·0 g.) was dissolved in sulphuric acid (7 ml.), and the mixture was set aside for 2 days and then poured into water. A red solid, probably a sulphate (0·84 g.), was deposited and this, recrystallised from aqueous ethanol and chromatographed in benzene on alumina (Spence " H," deactivated with 3% of 10% acetic acid), gave *ethyl* 3-*amino*-4-(*α-ethoxycarbonylbenzylidene*)-1,4-*dihydro*-1-*imino*-2-*naphthoate* (II) (0·31 g.), in pale yellow prisms (from ethanol), m. p. 255—258° (decomp.), 273° * (* here and below indicates a tube placed in the bath at 230°) (Found: C, 70·65; H, 5·8; N, 7·2; O, 16·7; OEt, 20·6. $C_{22}H_{22}N_2O_4$ requires C, 70·75; H, 5·7; N, 7·2; O, 16·4; 2EtO, 23·0%). The mother-liquors afforded a pale yellow solid (0·05 g.), m. p. 262—265° (decomp.), which sublimed at 230—235°/0·01 mm., giving a further quantity of the amine, m. p. 261—266° (decomp.), 271° * (Found: C, 70·7; H, 5·8; N, 7·2; O, 16·7; OEt, 20·5%).

The m. p. of the amine depended on the rate of heating; melting occurred at 230° after *ca.* 15 min. The compound was neutral to potentiometric titration with acid and with base in ethanol, and dissolved in concentrated hydrochloric acid but not appreciably in the 5N-acid.

(*b*) The ester (I) (2·75 g.) was kept in sulphuric acid (50 ml.) at room temperature for 24 hr., then ethanol was allowed to distil isothermally into the mixture. This (after 1 week) afforded to benzene the above amine (1·04 g.), m. p. 253° * (decomp.), and to ether a further quantity (407 mg.) of the amine, m. p. 257° * (decomp.), as thick lemon-yellow needles (Found: C, 70·5; H, 5·8; N, 7·0; O, 16·7; OEt, 19·8%). In subsequent preparations the cyclisation was carried out during 2 days, basification was with ammonia, and the precipitate was extracted (Soxhlet) with chloroform, chloroform eluting the amine, m. p. 254° * (decomp.) (1·69 g.), from alumina.

XUM

(*c*) *Isolation of ethyl* 3,5-*dihydro*-5-*imino*-2-*oxo*-1-*phenyl*-2H-*benz*[e]*indole*-4-*carboxylate* (III).—(i) In a condensation analogous to (*b*), when the isothermal distillation was prolonged for several weeks, a chloroform eluate gave material (1·14 g.) of m. p. 233—236° (decomp.), (from ethanol). This recrystallised from chloroform–ethanol; deep yellow prisms were first deposited and subsequently pale yellow needles began to separate. The crystallisation was interrupted at this point and the initial material [101 mg. of m. p. 226—230° (decomp.)], washed with chloroform and purified from ether–chloroform, afforded the orange-yellow *lactam* (74 mg.), m. p. 231—233° (decomp.) either in characteristic diamond-shaped prisms or in plates with bluntly pointed ends (Found: C, 73·2; H, 4·8; OEt, 11·6. $C_{21}H_{16}N_2O_3$ requires C, 73·2; H, 4·7; OEt, 13·1%). Further crystallisation from the ethanol–chloroform solution afforded the above-mentioned amine, m. p. 265° • (decomp.) (Found: C, 70·5; H, 5·8; OEt, 20·5. $C_{23}H_{22}N_2O_4$ requires C, 70·75; H, 5·7; 2EtO, 23·0%).

(ii) In a cyclisation analogous to (*a*), the mixture was poured into ice–sodium carbonate, giving a crude solid (0·22 g.), which, chromatographed on alumina, afforded a benzene eluate and an ether eluate; material from the latter sublimed at 190—210°/0·01 mm. and then crystallised from chloroform–ether, giving the lactam (21 mg.) in yellow plates, m. p. 234° (decomp.) (Found: C, 73·4; H, 4·8; N, 7·8. $C_{21}H_{16}N_2O_3$ requires N, 8·1%; cf. above). The benzene eluate decomposed extensively when sublimed at 240°; the residue, purified from chloroform–ether, afforded the lactam in orange-yellow rhombs (Found: C, 73·15; H, 4·7; N, 7·45; O, 15·4; OEt, 11·6. $C_{21}H_{16}N_2O_3$ requires O, 13·9%; cf. above).

Conversion of Ethyl 3-*Amino*-4-(α-*ethoxycarbonylbenzylidene*)-1,4-*dihydro*-1-*imino*-2-*naphthoate* (II) *into Ethyl* 3,5-*Dihydro*-5-*imino*-2-*oxo*-1-*phenyl*-2H-*benz*[e]*indole*-4-*carboxylate* (III).—The amine (II) (197 mg.) was refluxed for a short time in diphenyl ether, a trace of sodium was added, and the mixture was refluxed for 10 min., allowed to cool, and added to diethyl ether containing a little ethanol. The solid was collected and purified to give the lactam (48 mg.) in characteristic diamond-shaped plates, m. p. 233—235° (decomp.) (Found: C, 73·3; H, 4·8; N, 7·9; OEt, 12·6%).

When, however, the amine (211 mg.) was refluxed in diphenyl ether for 1·5 hr. it (92 mg.) was recovered [m. p. 268—270° • (decomp.)]; some darker material was also formed. Addition of ammonium chloride to this mixture gave similar results.

The amine (II) decomposed to a clear brown melt when kept at 230° under nitrogen for 20 min.; the dark brown gum did not give a crystalline product to ether–chloroform.

Ethyl 3,5-*Dihydro*-2,5-*dioxo*-1-*phenyl*-2H-*benz*[e]*indole*-4-*carboxylate* (V).—(a) Ethyl 3-amino-4-(α-ethoxycarbonylbenzylidene)-1,4-dihydro-1-imino-2-naphthoate (II) (350 mg.) in acetic acid was refluxed for 1·5 hr. Diluting the mixture with water gave, in quantitative yield, the *ester* in yellow rods (from aqueous acetic acid), m. p. 225—226° (Found: C, 73·1; H, 4·4; N, 4·2; O, 18·9; OEt, 9·6. $C_{21}H_{15}NO_4$ requires C, 73·0; H, 4·4; N, 4·1; O, 18·5; OEt, 13·0%).

The ester was also obtained in an unsuccessful attempt to convert the amine in acetic acid containing sodium acetate into a *p*-nitrophenylhydrazone; it had m. p. and mixed m. p. 226° (Found: N, 4·25%).

(b) Ethyl 3,5-dihydro-5-imino-2-oxo-1-phenyl-2*H*-benz[*e*]indole-4-carboxylate (28 mg.), in acetic acid, was refluxed for 1·5 hr. to yield the ester (22 mg.), m. p. and mixed m. p. 225—226°.

3,5-*Dihydro*-2,5-*dioxo*-1-*phenyl*-2H-*benz*[e]*indole*-4-*carboxylic Acid* (VI).—Ethyl 3-amino-4-(α-ethoxycarbonylbenzylidene)-1,4-dihydro-1-imino-2-naphthoate (II) (366 mg.) was refluxed in aqueous-ethanolic potassium hydroxide for 5 hr., to give the *acid* (from aqueous acetic acid) in red needles, m. p. 270° (decomp.) (218 mg.), which did not lose weight when dried at 150°/0·01 mm. (Found: C, 72·3; H, 3·4; N, 4·9; O, 20·1; OEt, Nil. $C_{19}H_{11}NO_4$ requires C, 71·9; H, 3·5; N, 4·4; O, 20·2%).

This acid (57 mg.), m. p. 271° (decomp.) and undepressed on admixture, was obtained similarly from ethyl 3,5-dihydro-2,5-dioxo-1-phenyl-2*H*-benz[*e*]indole-4-carboxylate (V) (0·2 g.).

Acetylation of Ethyl 3-*Amino*-4-(α-*ethoxycarbonylbenzylidene*)-1,4-*dihydro*-1-*imino*-2-*naphthoate*.—(*a*) The amine (II) (375 mg.) was saturated with keten during 0·5 hr. The mixture was set aside for 1 hr., and solvent was removed, giving the *acetyl derivative* (VII) (419 mg.), which separated from benzene–light petroleum in pale yellow needles, m. p. 256—259° (decomp.) [Found: C, 69·0, 69·0; H, 5·9, 5·5; N, 6·3, 6·6; O, 19·5; OEt, 18·1; Ac, 8·7 (Wenzel's H_2SO_4), 9·9 (methanolic NaOH 8, hr.; Dr. Zimmermann reported the formation of an alkaline distillate in this analysis); active H, 0·6. $C_{25}H_{24}N_2O_5$ requires C, 69·4; H, 5·6; N, 6·5; O, 18·5; 2EtO,

20·8; Ac, 10·0; 2H, 0·5. Calc. for $C_{27}H_{26}N_2O_6$: C, 68·3; H, 5·5; N, 5·9; O, 20·2; 2EtO, 19·0; 2Ac, 18·1%].

This derivative (258 mg.) was refluxed in acetic acid during 3 hr., then the mixture was diluted to turbidity with water, giving a solid (64 mg.). This was run in benzene on alumina from which chloroform eluted the acetyl derivative, m. p. 258—259·5° (from aqueous acetic acid) (38 mg.), of ultraviolet absorption identical with that of the original material (Found: C, 69·3; H, 5·6; N, 6·5; OEt, 17·6%).

(*b*) In another experiment the amine (II) (0·71 g.) in chloroform was saturated with keten during 4 hr.; evaporation and chromatography afforded a solid (0·46 g.) (from benzene), m. p. 180°, which (130 mg.), refluxed as above in acetic acid, yielded the acetyl derivative (68 mg.), m. p. 258° (Found: C, 69·45; H, 5·7; N, 6·5; OEt, 18·5; Ac, 5·2%). Recrystallisation (four times) of the solid from benzene–light petroleum failed to change the unsatisfactory melting behaviour, *viz.*, partial melting at 180°, resolidification and remelting in the 205—220° range, although the *benzene hemisolvate* of the diacetyl derivative was so obtained in homogeneous feathery pale yellow needles (Found: C, 70·3; H, 5·8; N, 5·7; OEt, 15·35; Ac, 9·1. $C_{27}H_{26}N_2O_6,\frac{1}{2}C_6H_6$ requires C, 70·2; H, 5·75; N, 5·45; 2EtO, 17·5; Ac, 16·7%), $\lambda_{max.}$ at 373, 270, 232 (infl. at 302) mμ (log ε 3·595, 4·458, 4·608, 3·65) (closely resembling the absorption of the monoacetyl derivative). The solvate (56·7 mg.) lost 3·8 mg. when dried at 185°/0·05 mm. (fused; drying at 160° for 1 hour caused a loss of only 1·5 mg.) (calc.: 4·3 mg.), to give *ethyl 4-diacetylamino-1-(α-ethoxycarbonylbenzylidene)-1,2-dihydro-2-imino-3-naphthoate*, m. p. 215° (Found: C, 67·8; H, 5·6; N, 6·1. $C_{27}H_{26}N_2O_6$ requires C, 68·3; H, 5·5; N, 5·9%).

The solid (94 mg.) was refluxed in methanolic sodium hydroxide during 6 hr.; the mixture afforded an acid, m. p. 166—167°, in pale yellow needles (53 mg.) (from aqueous acetic acid) which decomposed at *ca.* 150° under a vacuum to an orange gum. A different sample of lower purity was passed in aqueous acetic acid through a column of alumina to give (from aqueous acetic acid) an acid, m. p. 165—167°, orange-yellow needles which were dried at room temperature (Found: C, 64·7; H, 4·8; N, 5·3. Calc. for $C_{19}H_{13}NO_5,H_2O$: C, 64·6; H, 4·3; N, 4·0. Calc. for $C_{19}H_{12}N_2O_3,2H_2O$: C, 64·8; H, 4·6; N, 7·95%).

Reductive Acetylation of Ethyl 3-Amino-4-(α-ethoxycarbonylbenzylidene)-1,4-dihydro-2-naphthoate.—A mixture of the amine (1·03 g.), zinc dust (1·0 g.), and acetic anhydride (30 ml.) was refluxed for 15 hr. with occasional additions of further amounts of zinc. The supernatant liquid was filtered and diluted with water, giving a solid (1·2 g.), which (1 g.) was chromatographed on alumina from which benzene eluted the *acetyl derivative* (0·82 g.), m. p. 211—212° (from ethanol) [Found: C, 66·7, 67·2; H, 5·6, 5·6; N, 5·35, 5·2; O, 22·2; Ac, 18·3 (Wenzel's H_2SO_4), 22·1 (methanolic NaOH, 6 hr.); OEt, 16·1; active H, 0·08 (at 95°). Found, for a different sample: C, 67·0; H, 5·6; N, 5·5; O, 22·3. $C_{29}H_{30}N_2O_7$ requires C, 67·2; H, 5·8; N, 5·4; O, 21·6; 3Ac, 24·8; 2EtO, 17·4; H, 0·2. $C_{31}H_{32}N_2O_8$ requires C, 66·4; H, 5·75; N, 5·0; O, 22·8; 4Ac, 30·7; 2EtO, 16·1%]. Repetition of this experiment was on occasion unsuccessful, particularly when acetic acid was added to the reaction mixture. The ester failed to give the iodoform test [12] and when oxidised with chromic acid in acetic acid it did not yield a crystalline product. It was recovered (m. p. and mixed m. p.) after treatment of its warm chloroform solution with bromine.

Diethyl 7,9-Dihydro-5,9-di-imino-5H-dibenzo[c,g]carbazole-6,8-dicarboxylate (IX).—A solution of 2,5-di-(α-cyano-α-ethoxycarbonylmethylene)-3,4-diphenyl-3-pyrroline (VIII) (2·6 g.) in sulphuric acid was set aside for 10 days, then poured on ice and sodium carbonate. The solid so obtained (2·6 g.) was extracted with hot benzene, leaving a residue (0·3 g.); the extract was chromatographed on alumina (deactivated with 1% of 10% acetic acid) from which benzene eluted a deep yellow gum which (from chloroform–ethanol) gave the *ester* in orange-red plates (112 mg.), m. p. 267—268° (Found: C, 70·5; H, 5·15; N, 9·15, 9·25; O, 14·0; OEt, 18·0. $C_{28}H_{21}N_3O_4$ requires C, 71·1; H, 4·8; N, 9·6; O, 14·6; OEt, 20·4%).

Acetylation of Ethyl 1,3-Diamino-2-naphthoate.—Ethyl 1,3-diamino-2-naphthoate,[4] acetylated at <40°, gave a *monoacetyl derivative* in pale yellow needles (from aqueous ethanol), m. p. 161—162° (Found: C, 65·8; H, 5·95; N, 10·3; Ac, 15·0. $C_{15}H_{16}N_2O_3$ requires C, 66·2; H, 5·92; N, 10·3; Ac, 15·8%), which was also obtained in small yield from a reaction at a higher temperature. This, in chloroform, with keten afforded the *triacetyl derivative*, m. p. 169—170° [Found: C, 64·3; H, 5·7; N, 8·3; O, 22·1, 22·4; OEt, 12·9; Ac, 31·5; active H (in anisole), 0. $C_{19}H_{20}N_2O_5$ requires C, 64·0; H, 5·7; N, 7·9; O, 22·45; OEt, 12·6; 3Ac, 36·2%].

[12] Vogel, " Practical Organic Chemistry," 3rd edn., Longmans, London, 1957, p. 1069.

XUM

Action of Keten on α- and β-Naphthylamine.—The amine in chloroform was saturated with keten during 1·5 hr., the solvent was evaporated, and the residue was purified from benzene, the monoacetyl compounds, m. p. 157—158° and 132—134°, being obtained.

The author thanks the Research Committee of the University of New England for a grant, and Dr. W. Zimmermann and his staff for the microanalyses.

UNIVERSITY OF NEW ENGLAND,
ARMIDALE, N.S.W., AUSTRALIA. [*Received, October 21st,* 1960.]

---

401. *Dinitrogen Trioxide. Part IV.*[1] *Composition of the Vapour in Equilibrium with Liquid Mixtures of Nitrogen Dioxide and Nitric Oxide.*

By I. R. BEATTIE and A. J. VOSPER.

A study has been made of the vapour composition above liquid mixtures of nitrogen dioxide and nitric oxide. The vapour in equilibrium with a liquid containing equimolar amounts of nitrogen dioxide and nitric oxide is almost exclusively nitric oxide. The visible and near-ultraviolet spectra of some oxides of nitrogen in the gas phase and in solution are discussed. An all-glass circulating pump is described.

IN a previous paper[1] we reported the vapour pressure of liquid mixtures of nitric oxide and nitrogen dioxide. Although our results were generally in agreement with those of earlier workers,[2,3] the agreement with the data of Purcell and Cheesman[4] was poor. The British paper[4] contains the only available data on the composition of the gas in equilibrium with liquid mixtures of nitric oxide and nitrogen dioxide. We have re-investigated this system.

EXPERIMENTAL

Preparation of Reagents.—The preparation of nitric oxide and nitrogen dioxide has been described previously.[5]

Apparatus.—Most of the work was carried out in an all-glass apparatus in the absence of grease. In two experiments a greaseless diaphragm tap was included in the system. The liquid mixture of nitric oxide and nitrogen dioxide was contained in a cryoscope[6] which was connected to a spiral gauge used as a null-point instrument in the measurement of vapour pressures. The cryoscope was also connected to a pumping system for circulating the gases over the liquid mixture of nitrogen oxides and through an optical cell.

Fig. 1 shows the pump which was operated by means of three independent electromagnets acting on steel inserts. This pump was useful down to pressures of a few millimetres. The two valves were ground-glass ball-and-socket joints, while the plunger and barrel were obtained from a " Summit " interchangeable hypodermic syringe of 20 c.c. capacity. The glass of the syringe had a coefficient of linear expansion close to that of " Pyrex," so that direct sealing was possible. The pump would not operate in the presence of liquids as these caused sticking of the ball and socket valves.

Analysis of the Gases.—This was carried out at several different wavelengths in the range 4000—6000 Å, with a " Unicam " S.P. 500 ultraviolet spectrometer. The spectrometer was modified in that the cell compartment was replaced by a thermostatically controlled tank with plain " Pyrex " windows. Movement of the 5 cm. gas cell into or out of the light beam, for comparison with the reference cell, was accomplished by means of long inlet tubes connected to glass springs.

[1] Part III, Beattie and Vosper, *J.*, 1960, 4799.
[2] Whittaker, Sprague, Skolnik, and Smith, *J. Amer. Chem. Soc.*, 1952, **74**, 4794.
[3] Baume and Robert, *Compt. rend.*, 1919, **169**, 970.
[4] Purcell and Cheesman, *J.*, 1932, 826.
[5] Beattie and Bell, *J.*, 1957, 1281.
[6] Beattie, Bell, and Vosper, *J.*, 1960, 4796.

XUM

Spectrum of Nitrogen Dioxide.—We observed the spectrum of pure nitrogen dioxide by using a cell temperature of 135°, at which the vapour pressure of dinitrogen tetroxide would be negligible.

Discussion

The analysis of a mixture of nitric oxide, nitrogen dioxide, dinitrogen tetroxide, and dinitrogen trioxide by ultraviolet spectroscopy is simplified by the fact that nitric oxide is transparent above 2300 Å at normal pressures,[7] while dinitrogen tetroxide is transparent above 4000 Å.[8] The position with regard to dinitrogen trioxide is rather obscure. Early workers [9] found a band system in the 3000—4000 Å region which was initially attributed to dinitrogen trioxide. However, it was subsequently suggested that this spectrum was due either to selective enhancement of certain bands of the nitrogen dioxide molecule, or more probably to the presence of nitrous acid which would result if the reacting gases

Fig. 1. *The all-glass circulating pump.*

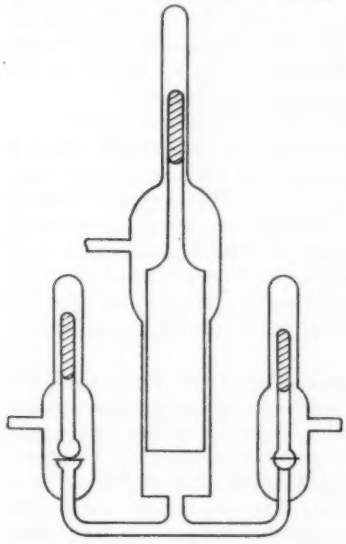
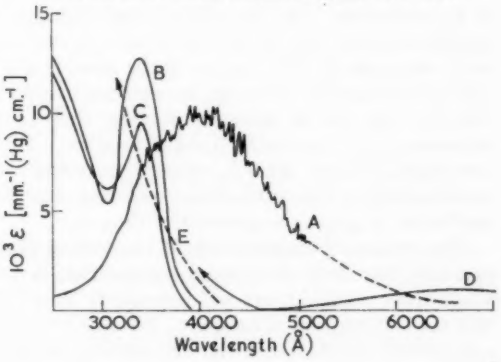


Fig. 2. *The spectrum of certain oxides of nitrogen in the gas phase and in solution*: A, *nitrogen dioxide*; B, *dinitrogen tetroxide in cyclohexane*; C, *dinitrogen tetroxide in the gas phase*; D, *dinitrogen trioxide in toluene at* −80°; E, *dinitrogen trioxide in the gas phase*. (The curve from the lower arrow head increases rapidly to >130.)



were not perfectly dry.[10] Although there has been some support for the enhancement theory,[11] D'Or and Tarte [12] have shown that " dry " gas mixtures of nitric oxide and nitrogen dioxide show only a trace of this banded system unless the apparatus has been baked out under a high vacuum, when a continuous absorption appears below 3000 Å. This work has been supported [13] by a study of the isotopic shift effect for the band system, where H_2O or D_2O was used with a mixture of nitric oxide and nitrogen dioxide. Melvin and Wulf [10] note that " the absorption in the red or orange that leads to the blue colour of liquid N_2O_3 has not yet been observed " in the gas.

The spectrum of dinitrogen trioxide in several solvents [14] has shown the presence of a

[7] Jenkins, Barten, and Mulliken, *Phys. Rev.*, 1927, **30**, 150.
[8] Hall and Blacet, *J. Chem. Phys.*, 1952, **20**, 1745.
[9] Melvin and Wulf, *Phys. Rev.*, 1931, **38**, 2294.
[10] Melvin and Wulf, *J. Chem. Phys.*, 1935, **3**, 755.
[11] Newitt and Outridge, *J. Chem. Phys.*, 1938, **6**, 752.
[12] D'Or and Tarte, *Bull. Soc. roy. Sci. Liège*, 1951, 685; *Bull. Soc. chim. belges*, 1950, **59**, 365.
[13] Porter, *J. Chem. Phys.*, 1951, **19**, 1278.
[14] Mason, *J.*, 1959, 1288, and references therein.

XUM

weak absorption maximum at about 7000 Å and an intense absorption, similar to that in the gas phase, below 3500 Å. Fig. 2 shows the spectrum of several nitrogen oxides in the gas phase in the region 3000—7000 Å. Whittaker *et al.*[15] have suggested that nitrogen dioxide has the same spectrum (and extinction coefficients) in solution as in the gas phase. Addison and Sheldon [16] have measured the absorption spectrum of dinitrogen tetroxide in several solvents. In non-co-ordinating solvents the spectrum is very similar to that in the gas phase. It is reasonable to suppose that the spectrum of dinitrogen trioxide in the gas phase will be similar to that of a solution of dinitrogen trioxide. If we assume that dinitrogen trioxide is fully associated in toluene at −80° it is possible to calculate extinction coefficients. This has been done, and the results are shown in Fig. 2.

Kaufmann and Kelso,[17] while studying the thermal decomposition of nitric oxide, observed the spectra of two mixtures initially containing the same quantities of nitrogen(IV) oxide, but in one case containing an excess of nitric oxide to one atmosphere total pressure and in the other an excess of oxygen to the same total pressure. If no dinitrogen trioxide were formed the two spectra would be identical. By using the given spectra, plus the equilibrium constants for the dissociation of dinitrogen tetroxide [18] and dinitrogen trioxide,[5] it is possible to calculate approximately the extinction coefficients of dinitrogen trioxide in the range 3500—4000 Å. These results are included in Fig. 2, where it is clear that the gas-phase spectrum shows resemblances to that obtained in solution.

The intensity of the band around 7000 Å for solutions of dinitrogen trioxide is low, even at its maximum. In view of the small quantities of dinitrogen trioxide usually found in equilibrium mixtures of nitrogen oxides at room temperature this compound is not likely to be important in the analysis of the gases in the visible region. However, for relatively high pressures of nitric oxide the amount of dinitrogen trioxide may become comparable with the amount of nitrogen dioxide, and in the region of 7000 Å could cause quite erroneous analytical results if not allowed for. Our analyses, carried out at several different wavelengths above 4000 Å, showed no trend with wavelength. We assume that the combination of low extinction coefficient and low concentration of dinitrogen trioxide enables us to ignore the presence of the gas.

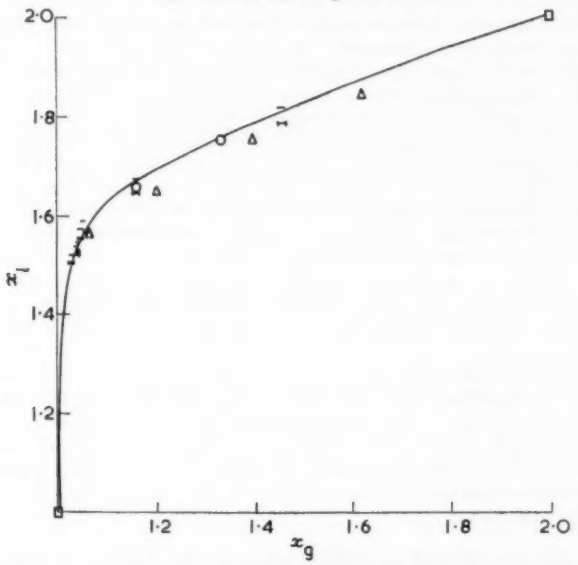
The results of examination of the vapour-phase composition are shown in the Table and take the form of a liquid composition, a vapour pressure, and a gas composition. These three variables are not necessarily simply related. Inspection of the Table shows that the composition of the gas x_g (where x refers to composition in terms of NO_x) is almost independent of the particular combination of pressure and composition of the liquid x_l, *for any given sample in our apparatus*. In view of the fact that each sample was studied in a closed system, the total composition for any given sample is constant. It is therefore possible to construct a graph such as that shown in Fig. 3, where values of the liquid composition (interpolated to a pressure of either 20 or 50 cm.) are plotted atainst the gas composition. It is not easy to assess the errors in the gas-phase composition, but systematic errors are not likely to occur except in so far as equilibrium-constant data are used for the calculations. The length of the horizontal lines indicates the spread of our analytical figures for the gas phase at any given total composition. The error in x_l is at most $\pm 0{\cdot}002$. The line drawn on the graph is the mean of our results and agrees in a satisfactory manner with the results obtained from the data of Purcell and Cheesman [4] (at 76 cm.).

It appears from these results that the composition of the vapour above liquid mixtures of nitric oxide and nitrogen dioxide is nearly independent of temperature for a particular liquid composition. Further, the vapour above " pure " dinitrogen trioxide is almost exclusively nitric oxide. These results, taken together with the vapour-pressure and

[15] Whittaker, *J. Chem. Phys.*, 1956, **24**, 780; Steese and Whittaker, *ibid.*, p. 776.
[16] Addison and Sheldon, *J.*, 1958, 3142.
[17] Kaufmann and Kelso, *J. Chem. Phys.*, 1955, **23**, 1702.
[18] Giauque and Kemp, *J. Chem. Phys.*, 1938, **6**, 40.

magnetic results[1] on this system, support the suggestion that nitric oxide has a low physical solubility in dinitrogen trioxide.

FIG. 3. *The composition of the vapour, x_g, against the composition of the liquid, x_l, for mixtures of nitric oxide and nitrogen dioxide.*



|——| 20 cm. pressure. —— 50 cm. pressure. ○ Two points with diaphragm taps (see Table).
△ Data from Purcell and Cheesman. □ Pure nitric oxide or pure nitrogen(IV) dioxide.

Our results for the extinction coefficients of nitrogen dioxide (obtained at 135°) are in good agreement with those of earlier workers for lower temperatures, where equilibrium-constant data are necessary.

Vapour pressure, liquid composition, and gas composition for mixtures of nitrogen dioxide and nitric oxide.

Sample	x_l	Pressure (mm.)	x_g	Sample	x_l	Pressure (mm.)	x_g
1	1·747 *	76·5 *	1·335 *	6	1·544	41·0	1·054
2	1·656 *	23·9 *	1·160 *		1·551	143·4	1·049
3	1·785	91·0	1·477		1·559	275·3	1·045
	1·792	182·7	1·461		1·570	477·1	1·043
	1·803	339·3	1·446	7	1·528	75·9	1·045
	1·816	495·8	1·451		1·532	229·0	1·041
4	1·644	27·4	1·160		1·538	376·2	1·040
	1·654	179·8	1·163		1·551	562·4	1·040
	1·663	338·2	1·159	8	1·521	187·4	1·047
	1·676	552·6	1·163		1·532	399·7	1·036
5	1·560	17·3	1·056		1·537	479·4	1·038
	1·564	88·7	1·057	9	1·502	112·2	1·032
	1·572	229·0	1·053		1·506	209·4	1·028
	1·589	478·7	1·051		1·513	352·0	1·030
					1·521	527·7	1·028
					1·527	636·0	1·025

* Apparatus contained a greaseless diaphragm tap.

We thank the Royal Society for a grant to purchase a Unicam S.P. 500, and the D.S.I.R. for a grant to A. J. V.

KING'S COLLEGE (UNIVERSITY OF LONDON),
STRAND, LONDON, W.C.2.

[*Received, October 27th*, 1960.]

XUM

402. *Electron-donor and -acceptor Complexes with Aromatic Systems. Part VI.* Complexes of Nonacyclic Aromatic Molecules.*

By N. D. Parkyns and A. R. Ubbelohde.

Solid complexes of the nonacyclic molecules isoviolanthrene and isoviolanthrone have been prepared by vacuum-line techniques. Electron-acceptors used with both aromatic molecules included iodine, iodine monochloride, titanium tetrachloride, and aluminium chloride. Electron-donors used with isoviolanthrene included sodium and potassium.

Both donor and acceptor complexes of isoviolanthrene show very marked lowering of activation energies, accompanying a marked increase of dark-current conductivities. Acceptor complexes of isoviolanthrone show little change in activation energy, but some increase of conductivity over that of the parent aromatic molecule. Density measurements show marked electrostriction of complexes between isoviolanthrene and the electron-donor atoms, sodium or potassium. Little or no electrostriction is observed on complex formation with the acceptors, titanium tetrachloride, aluminium trichloride, or iodine, though there is some contraction with iodine monochloride.

From the observations made, it seems likely that any polarisation bonding between these aromatic molecules and electron-acceptors is weak, and is of the $n \longrightarrow \upsilon$ type with isoviolanthrone but of the $\pi \longrightarrow \upsilon$ type with isoviolanthrene. Polarisation bonding is stronger between electron-donors and isoviolanthrene, and appears to be predominantly ionic in nature; the quasi-metallic behaviour of these complexes may be interpreted in terms of electron-band theory.

It is now well established that aromatic molecules can behave as semi-conductors. In some cases, *e.g.*, anthracene,[1] the specific resistance ρ is extremely high, of the order of 10^{16} ohm cm. at room temperature. The thermal activation energy ε controlling the conduction process, as defined by the equation $\rho = \rho_0 \exp \varepsilon/kT$, usually lies between 1 and 2 ev. Formation of polarisation-bond addition complexes between electron-donors and aromatic molecules has been found to reduce both the specific resistance and the activation energy very markedly (cf. Parts I—V of this series). This has been interpreted on the basis of "quasi-metallic" polarisation bonding in the solids. Somewhat analogous complexes are formed between electron-acceptors, such as bromine, and heterocyclic tricyclic aromatic hydrocarbons (Parts III—V). With perylene and other larger aromatic molecules, the lowering of electrical resistance which is observed on formation of complexes with bromine has been reported to be even more striking,[2] but these results are difficult to interpret owing to complications caused by electrophilic substitution by bromine.

Increases of electrical conductance on formation of complexes are of inherent interest for characterising electron states in aromatic molecules, and also because closely related phenomena are found in crystal compounds of graphite.[3,4] Graphite may be regarded in this respect as an aromatic macromolecule in a homologous series of which benzene is the first member.

Isoviolanthrene † (I) is probably the largest polynuclear aromatic molecule whose quinone, isoviolanthrone (II), is readily available as a dyestuff, and which can still be

* Parts I—V, *J.*, 1954, 720; 1955, 4089; 1957, 911, 918, 982.

† To be termed dehydroviolanthrene by the I.U.P.A.C. 1957 Rules.

[1] Northrop and Simpson, *Proc. Roy. Soc.*, 1956, *A*, **213**, 124; Mette and Pick, *Z. Phys.*, 1953, **134**, 566.

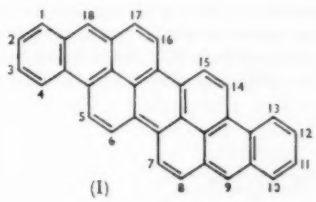
[2] Akamatu, Inokuchi, and Matsunaga, (*a*) *Nature*, 1954, **173**, 168; (*b*) *Bull. Chem. Soc. Japan*, 1956, **29**, 213.

[3] McDonnell, Pink, and Ubbelohde, *J.*, 1951, 191.

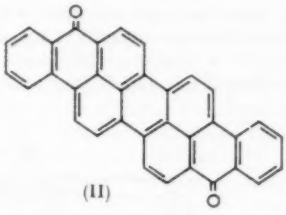
[4] Ubbelohde, Blackman, and Mathews, *Nature*, 1959, **184**, 454.

prepared in the highly pure condition [5] necessary for a study of the electronic properties. The present paper describes studies of solid donor and acceptor complexes formed by these two nonacyclic aromatic molecules.

Choice of suitable electron-accepting molecules was made from species unlikely to cause nuclear substitution, and at first fell on aluminium chloride, iodine monochloride, and titanium tetrachloride. The first two of these were known to produce marked lowering of specific resistance on formation of crystal compounds with graphite.[6] However, on trial, it was found that iodine monochloride causes substitution by chlorine in isoviolanthrene, so that iodine was used in its place to obtain a closely analogous complex. Titanium tetrachloride has been used in solution to prepare positive ions of diphenylpolyenes,[7] and complexes with *cis*- and *trans*-stilbene have also been reported.[8] Brass *et al.*[9] have isolated solid complexes between metal halides and a variety of hydrocarbons and quinones; these products are probably related to those dealt with in this paper, but no studies of the relevant properties appear to have been carried out.



(I)


(II)

Choice of electron-donors fell in the first place on alkali-metal atoms; potassium and sodium proved suitable, but experimental difficulties precluded the use of lithium in the procedures described below.

Few theoretical calculations have yet been published about the electronic properties of either isoviolanthrene or its quinone. Preliminary calculations [10] indicate that the positions of highest free-valency number are 9 and 18 (I.U.P.A.C. numbering given above); these positions are analogous to the *meso*-positions in anthracene, and it is interesting that the free-valency number calculated for them is 0·540 as compared with 0·520 for the *meso*-positions in anthracene. On the basis of a general parallelism between high free-valency and chemical reactivity, isoviolanthrene would be expected to be even more reactive chemically than anthracene. Some of its protonation and oxidation reactions in acid solution have been discussed on this basis in a previous paper.[5]

The preparation of solid adducts of graphite with electron donors and acceptors by vacuum-line techniques is well known. Analogous procedures starting with the smaller aromatic molecules have not been previously reported, though once solid complexes have been formed with alkali-metal atoms their composition can be modified by vacuum-sublimation (Part II). Compounds (I) and (II) have vapour pressures sufficiently low to permit the use of vacuum-line techniques *ab initio*, as recorded below. Measurements were carried out on the dark-current electrical conductance of the polycrystalline powders.[5] Densities were also measured, as described below. Although determinations of thermoelectric power were hampered by experimental difficulties, its sign and approximate magnitude were established in as many cases as possible, because of the information this gives about the predominant charge-carrier species.

[5] Parkyns and Ubbelohde, *J.*, 1960, 4188.
[6] Blackman, Mathews, and Ubbelohde, *Proc. Roy. Soc.*, 1960, *A*, **256**, 15.
[7] Van der Meij, Thesis, Amsterdam, 1958.
[8] Brackmann and Plesch, *J.*, 1953, 1289.
[9] Brass and Tengler, *Ber.*, 1931, **64**, 1650; Brass and Fanta, *Ber.*, 1936, **69**, 1.
[10] Pullman, Proc. Third Conference on Carbon, Pergamon, Buffalo, 1959, p. 3.

The behaviour of electron-donors and -acceptors could be compared for the hydrocarbon (I); but, for the quinone (II), only electron-acceptor complexes could be prepared if decomposition was to be avoided. In a number of cases of complex formation striking changes in electrical properties are observed. These are discussed below.

Experimental

Preparation of Titanium Tetrachloride Complexes.—Attempts to prepare these along the same lines as the aluminium chloride adducts (see below) proved inconvenient; the apparatus finally developed is shown in Fig. 1. The small container, fitted with a B24 cone, was chilled in liquid nitrogen, and liquid titanium tetrachloride (5 ml.) was added. This immediately froze and was then easily transferred to the apparatus without hydrolysis. The apparatus was evacuated and the first bulb C was chilled to trap titanium tetrachloride, which distils off at room temperature. When bulb C was almost full the first constriction was sealed off without admission of air. The distillation was repeated into bulb B by a similar method, and the apparatus was sealed at the constrictions between the tubes carrying bulbs C and B and between the reaction tube A and the evacuating pumps. The titanium tetrachloride obtained in bulb B in this way was clear and colourless and evaporated without yielding bubbles of hydrogen chloride. Reaction was carried out by putting the reaction tube A containing the quinone or hydrocarbon into a furnace at 200° and gently warming bulb B. After a few hours the final constriction (between A and B) was sealed and the solid was allowed to reach equilibrium at

Fig. 1.

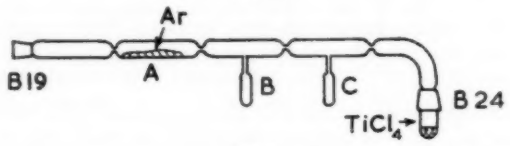
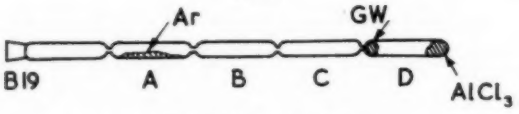


Fig. 2.



Preparative apparatus.
Ar = *Aromatic compound.* GW = *Glass wool.*

250° during 12 hr. Both quinone and hydrocarbon complexes were black and showed no other appearance of reaction [Found, for quinone (II): C, 49·85; H, 2·9; TiO_2, 18·3. Calc. for $C_{34}H_{16}O_2(TiCl_4)_{1\cdot87}$: C, 50·4; H, 2·0; TiO_2, 18·5. Found, for hydrocarbon (I): C, 60·4; H, 2·8; TiO_2, 15·25. Calc. for $C_{34}H_{18}(TiCl_4)_{1\cdot29}$: C, 60·0; H, 2·7; TiO_2, 15·4%). The analyses were subject to experimental difficulties but the ratio TiO_2 : hydrocarbon appears to be reliable.

Preparation of Quinone–Iodine Monochloride Complexes.—These were prepared analogously to the bromine–benzoquinoline complexes, as described in Part V. The composition of the complexes was established by direct weighing. No feature of the preparation calls for special comment; the reaction was speeded by warming to about 30° because of the low vapour pressure of iodine monochloride. The colour of the complexes was very similar to that of complexes with aluminium chloride.

Preparation of Hydrocarbon–Iodine Complexes.—Complexes of the hydrocarbon were not prepared with iodine monochloride because electrophilic substitution took place. For comparison a complex was made with iodine, by the method adapted for violanthrene by Akamatu, Inokuchi, and Matsunaga [2b] from that of Brass and Clar.[11] Compositions were calculated from the gain in weight.

Preparation of Aluminium Chloride Complexes.—Because of the possibility of formation of a Friedel–Crafts type of adduct, the preparation of these complexes was carried out both *in vacuo* and in a stream of hydrogen chloride. However, no obvious difference in properties could be

[11] Brass and Clar, *Ber.*, 1939, **72**, 1882.

established in the two sets of products. The formation of two different adducts, as described by Baddeley,[12] may perhaps require the presence of a solvent. Water and oxygen were scrupulously kept from contact with the final product, which appeared to be somewhat susceptible to hydrolysis so that analysis proved difficult.

About 0·5 g. of purified quinone or hydrocarbon was placed in tube A of a vacuum reaction system (Fig. 2). Crude aluminium chloride (B.D.H.) was placed in the far end (then open) of tube D which was next sealed. The whole apparatus was evacuated to 10^{-3} mm. Hg and the aluminium chloride was heated at about 120° so that it distilled into tube C. The lumps tended to decrepitate; to prevent resulting contamination glass wool was placed between tubes D and C. After this distillation, tube D was sealed off from tube C at the constriction and the aluminium chloride was redistilled into tube B. Careful control of the distillation made it possible to obtain aluminium chloride in tube B coloured only faintly yellow. The apparatus was then sealed at the constrictions between tubes C and B, and between tube A and the vacuum pump, and reaction was brought about by heating both tubes A and B at 200° for about 12 hr. This left an excess of aluminium chloride in the reaction tube, which was distilled off by raising the temperature of tube A to 220° and lowering that of tube B to 180°. The reaction tube A was then sealed off and heated to 250° for 12 hr. to ensure uniform equilibration throughout the solid product. The quinone adduct was reddish-violet; the hydrocarbon had a dark violet sheen. Although analysis of these complexes was not completely consistent the complexes fit best to compositions indicated in Tables 1 and 2.

The preparations were repeated under a stream of dry hydrogen chloride, obtained by dropping concentrated sulphuric acid on to solid ammonium chloride and bubbling the gas through concentrated sulphuric acid. The reaction tube was very similar to that of Fig. 2 but the tube was not evacuated and the gas was admitted through tube D. The quinone or hydrocarbon was heated at 180° and the aluminium chloride containing hydrogen chloride was passed over it to ensure that the reactants were present in excess. After complete reaction, the tube was sealed off and the contents were homogenised as before.

Preparation of Alkali-metal–Hydrocarbon Complexes.—In previous work, preparation of alkali-metal adducts of hydrocarbons was carried out in ethereal solution. This process is greatly accelerated by using the cavitating effect of ultrasonic activation (cf. Part V). In the present case, however, because of the low solubility of isoviolanthrene even in relatively high-boiling ethers such as 2,2′-dibutoxydiethyl ether (b. p. 255°), the method previously described was impracticable. On the other hand, the low vapour pressure of the hydrocarbon makes feasible preparation by direct addition of alkali-metal vapour to the solid hydrocarbon. Details of the experimental procedure, which are analogous to those used for potassium–graphite,[13] will be described in Part VII of this series.

Complexes of relatively high metal content, for example, $K_{4\cdot05}Ar$, and $K_{4\cdot55}Ar$, were normally obtained, but lower metal contents could be attained by using lower temperatures and shorter exposures to alkali-metal vapour. As in the case of powdered potassium–graphite,[3] all the complexes were immediately decomposed by water and many were pyrophoric in air. All appeared black.

Analysis was effected by weighing 0·1—0·2 g. of powder into a stoppered bottle under nitrogen and decomposing it cautiously with slightly damp ether to which ethanol was added if necessary. The decomposed complex was boiled with 1 : 1 aqueous ethanol to complete the reaction. The solid was filtered off in a sintered-glass crucible, dried at 110°, and weighed. It was assumed to be predominantly the dihydro-derivative of compound (I), on the basis of the known reactions of other hydrocarbon–alkali-metal adducts with water.[14] The product obtained from metal-rich complexes was insoluble in sulphuric acid, presumably because the 9,18-positions were blocked by hydrogen. Reaction may have produced some tetrahydro-product, but its presence or that of other hydrogenation products would hardly affect calculations of the composition. The filtrate was acidified with sulphuric acid and evaporated to dryness under a 250 w infrared lamp. Any remaining organic matter was oxidised with nitric and sulphuric acid, and the alkali metal was weighed as the metal hydrogen sulphate. In all cases agreement within 1% was obtained between the two methods of calculation; the latter was probably the more accurate.

[12] Baddeley, *Quart. Rev.*, 1954, **8**, 355.
[13] Fredenhagen, Cadenbach, and Suck, *Z. anorg. Chem.*, 1929, **178**, 333.
[14] Hoijtink, *Rec. Trav. chim.*, 1957, **76**, 885.

XUM

Most complexes were attacked by water or oxygen, so that, after preparation *in vacuo*, handling was done in a completely inert atmosphere. Details will be described in Part VII, along with the methods by which these labile compounds were transferred to cells for electrical measurements and to weighing bottles for analysis and density determinations.

Results

Densities.—Densities of the complexes are shown in Table 1, together with relevant molar volumes. In the calculations, molar volumes of the parent aromatic compounds were obtained from direct pyknometry. For the inorganic adducts the following molar volumes (c.c.) were assumed: $TiCl_4$ 110, $AlCl_3$ 109, ICl 51·1, K(metal) 45·4, Na(metal) 23·7.

Table 1. *Densities and molar volumes of complexes.*

Arom. mol. (Ar)	Complex composition ArX_m	Density (g./c.c.)	Theoretical molar volumes: Arom. mol. Ar	Inorg. adduct	Total V_1	Exp. molar vol. (V_2; c.c.)	$V_2 - V_1$ (ΔV; c.c.)
Quinone	(Pure)	1·47	—	—	—	310	—
	$(AlCl_3)_{3\cdot7}$	1·87	310	203	513	508	−5
	$(TiCl_4)_{1\cdot87}$	1·56	310	216	516	520	+4
	$(ICl)_{1\cdot49}$	1·93	310	86	396	378	−18
Hydrocarbon	(Pure)	1·47	—	—	—	290	—
	$(TiCl_4)_{1\cdot29}$	1·55	290	142	432	433	+1
	$I_{1\cdot53}$	1·89	290	39	329	327	−2
	$K_{4\cdot55}$	1·76	290	206	496	343	−153
	$K_{4\cdot05}$	1·75	290	184	474	333	−141
	$K_{1\cdot43}$	1·59	290	64	354	303	−51
	$Na_{2\cdot37}$	1·51	290	56	346	318	−28
	$Na_{0\cdot31}$	1·49	290	7	297	291	−6

Table 2. *Specific resistance parameters for addition complexes of compounds* (I) *and* (II).

Arom. mol. (Ar)	Complex ArX_m	$\rho_{20°}$ (ohm cm.)	ρ_0 (ohm cm.)	ε (ev)	Thermoelectric power (μv/°c)
Quinone	(Pure)	$3\cdot2 \times 10^{14}$ (av.)	520 (av.)	0·68	—
	$(AlCl_3)_{2\cdot7}$	$2\cdot6 \times 10^{12}$	13	0·65	—
	$(AlCl_3)_{2\cdot7}$ *	$2\cdot5 \times 10^{12}$	5·9	0·67	—
	$(TiCl_4)_{1\cdot87}$	$3\cdot0 \times 10^{10}$	0·69	0·64	—
	$(ICl)_{3\cdot73}$	$1\cdot1 \times 10^{9}$	1·9	0·49	—
	$(ICl)_{1\cdot90}$	$2\cdot2 \times 10^{8}$	15	0·47	—
	$(ICl)_{1\cdot45}$	$4\cdot5 \times 10^{11}$	7·1	0·62	—
Hydrocarbon	(Pure)	$3\cdot6 \times 10^{14}$	20	0·81	—
	$(AlCl_3)_{2\cdot2}$	36	0·7	0·11	—
	$(AlCl_3)_{2\cdot3}$ *	800	3·2	0·14	—
	$(TiCl_4)_{1\cdot29}$	354	2·6	0·13	—
	$I_{1\cdot52}$	580	7·6	0·11	−300
	$K_{4\cdot35}$	27	8·9	0·030	−20
	$K_{4\cdot05}$	100	3·7	0·083	−10
	$K_{1\cdot42}$	2600	5·2	0·014	—
	$Na_{2\cdot37}$	61	10	0·048	−10
	$Na_{0\cdot31}$	$3\cdot1 \times 10^{5}$	2·6	0·21	—

* Prepared under HCl.

Table 3. *Relative changes in conduction parameters on complex formation.*

	$\varepsilon/\varepsilon_{(parent)}$	$\rho_0/\rho_{0(parent)}$		$\varepsilon/\varepsilon_{(parent)}$	$\rho_0/\rho_{0(parent)}$
	Quinone complexes			Hydrocarbon complexes	
$(AlCl_3)_{3\cdot7}$	0·96	0·025	$AlCl_3)_{2\cdot2}$ *	0·14	0·03
$(AlCl_3)_{3\cdot7}$ *	0·98	0·011	$(AlCl_3)_{2\cdot3}$	0·17	0·16
$(TiCl_4)_{1\cdot87}$	0·94	0·001	$(TiCl_4)_{1\cdot29}$	0·16	0·13
$(ICl)_{0\cdot45}$	0·91	0·014	$I_{1\cdot52}$	0·14	0·38
$(ICl)_{1\cdot90}$	0·69	0·029	$K_{1\cdot43}$	0·17	0·26
$(ICl)_{3\cdot73}$	0·72	0·003	$K_{4\cdot05}$	0·10	0·19
			$K_{4\cdot55}$	0·04	0·45
			$Na_{0\cdot31}$	0·26	0·13
			$Na_{2\cdot37}$	0·06	0·50

* Prepared under HCl.

XUM

Resistance Parameters.—All complexes were found to obey the general equation:

$$\log_{10} \rho = \log_{10} \rho_0 + \varepsilon/2{\cdot}303kT$$

Values of ε and ρ_0 were obtained in the usual way from graphical plots. In Table 2 values of $\rho_{20°}$, ρ_0, and ε are shown for all the complexes.

Table 3 illustrates these changes on a relative basis so that relations can be more easily seen.

Discussion

One of the most striking results of this investigation is that extremely low activation energies are found with some of the hydrocarbon complexes with alkali metals. These solids are almost metalloid in character. In order to visualise these and other results in perspective, it is useful to discuss probable bond structures of the complexes and then to examine their bearing on the electronic properties.

Donor-acceptor Complexes of Aromatic Molecules.—Much attention has been paid to the " polarisation bonds " (Parts I—V) between aromatic molecules and electron-donors or -acceptors. For interpretation of the results so far available, probably the most satisfactory theoretical treatment is due to Mulliken.[15] An alternative suggestion by Dewar,[16] to explain the formation of complexes between electrophilic reagents and the π-electrons of double bonds, will not be discussed here. Mulliken's description has as basic feature contributions to the polarisation bond in a complex, both from the " no-bonding " ground state and from excited states in which charge-transfer has occurred. A solid adduct molecule may form polarisation bonds with more than one neighbouring aromatic molecule, provided these are suitably located in space. This faculty leads to the possibility of the adduct forming a " polarisation bridge " between neighbouring aromatic molecules. An immediate distinction is apparent between complexes formed by the two molecules, isoviolanthrone and isoviolanthrene, with electron-acceptors. In isoviolanthrone the more or less localised " lone pair " electrons of the oxygen form localised polarisation bonds with electron-acceptors such as aluminium chloride, and these are quite stable. Unless the crystal structure happens to be favourable, only one such bond can be formed by any one adduct molecule, and there are no polarisation-bond bridges. Table 1 shows that electrostriction is weak with this type of complex. Some effect of this polarisation bonding on the electronic properties may be inferred from Tables 2 and 3.

Isoviolanthrene forms a quite different class of complex with electron-acceptors. Since no lone-pair electrons are available, charge transfer must occur from the π-electron system; the polarisation bonds are described by Mulliken as $\pi \longrightarrow v$. The possibilities of forming polarisation bonds with more than one neighbouring aromatic molecule appear to be much greater. From the free-valency numbers positions of likely attachment of electrophilic groups would be 9 and 18, with 1, 8, 10, and 18 somewhat less reactive. The maximum uptake m of electron-accepting adduct groups in this type of complex, ArX_m, is probably determined, not only by free-valency number, but also by steric factors. With most electron-acceptors the first pronounced threshold at $m = 2$ does not appear to have been reached. In the absence of *X*-ray data it is not yet clear whether this represents an approach to an uptake of two molecules. Electrostriction in this group of complexes appears to be weak (Table 1).

Electron-donor Complexes.—In Mulliken's notation adducts of alkali-metal atoms with the hydrocarbon (I) appear to present extreme forms of the $\sigma \longrightarrow \pi$-type of complex. For the highly coloured solutions obtained by reaction of aromatic hydrocarbons dissolved in ethereal solvents with alkali metals, various lines of evidence suggest that aromatic mono- and di-negative ions are present.[17] In fairly dilute solutions ($<10^{-3}$M), no ion-pair

[15] Mulliken, *J. Amer. Chem. Soc.*, 1952, **74**, 811; *J. Phys. Chem.*, 1952, **56**, 801.
[16] Dewar, *Bull. Soc. chim. France*, 1951, **18**, 71.

XUM

association has been detected [17] and electron transfer may be assumed to be complete. In the solid state, neighbouring molecules are much more important. Evidence previously reviewed (Parts I, II, V) suggests that the crystal lattice is predominantly ionic, but that the degree of electron transfer from the *s*-electron shell of the alkali metal to the π-aromatic system is not quite complete. A partly covalent character of the polarisation bond for such complexes gave an explanation of both the strong electrostriction and the marked electrical conductivity of these solids. The present results support and extend these conclusions.

If the adduct with an alkali metal is fully salt-like, the observed molar volume would be expected to be less on conversion of metallic atoms into ions. The specific volume is assumed to be $\frac{4}{3}\pi r^3$ Å^3. For potassium ions the ion contact radius [18] assumed is $r = 1{\cdot}33$ Å, and for sodium ions 0·95 Å. A small expansion δ would be expected for the conversion of one molecule of aromatic hydrocarbon into the negative ion Ar^{m-}. If the free space in the hypothetical close-packed salt $Ar^{m-}X^{+}_{m}$ is assumed to be comparable with that in the parent hydrocarbon, as seems reasonable in view of the structure, the observed shrinkage $\Delta V = V_2 - V_1$ may be compared with the theoretical shrinkage

$$\Delta V_0 = -Nm\delta + m(V_{\text{metal}} - V_{\text{ion}})$$

If bonding were completely ionic, ΔV_0 would be slightly smaller than ΔV, owing to the term in δ. For more nearly metallic bonding, ΔV would be much smaller than the theoretical shrinkage ΔV_0. It can be seen from Table 4 that the experimental findings

TABLE 4. *Apparent expansion on forming salt-like adducts,* $Ar^{m-}X^{+}_{m}$.

m of adduct	$(\Delta V_0 - \Delta V)$ (Å^3)	$(\Delta V_0 - \Delta V)/m$	*m* of adduct	$(\Delta V_0 - \Delta V)$ (Å^3)	$(\Delta V_0 - \Delta V)/m$
	Potassium			Sodium	
1·42	8	5·6	0·31	2	6·4
4·05	31	7·7	2·37	39	16·4
4·55	43	9·4			

agree as well as can be expected with the assumption of a model that is approximately salt-like when the concentration of alkali metal is low, and becomes more metallic as this concentration increases.

Electronic Properties.—(i) From Tables 2 and 3 the conclusion is that, with the quinone, electron-acceptors show definite but comparatively small changes in the conductance parameters. This can be understood if conductivity in these aromatic solids is associated with systems of π-electrons, since the formation of local $n \longrightarrow v$ adducts at the quinone-oxygen atoms would not be expected to introduce more than second-order effects within the π-systems. Further, with iodine chloride no significant change in ε is observed beyond $m \sim 1{\cdot}9$, indicating that even after $n \longrightarrow v$ complex formation has proceeded to completion, the excess of adduct does not perturb the π-electron systems to any marked extent.

(ii) Electron-acceptors cause much more profound changes in adducts with the hydrocarbon. The remarkably low activation energies recorded in Table 3 all lie around 0·15 ev and suggest a common feature in the conductance process of the various solids. From the ready formation of R^+ or R^{2+} ions by the hydrocarbon (I) in strongly acid solutions [5] a corresponding process seems likely in solid adducts with electron-acceptors, though the absence of marked electrostriction (Table 1) is evidence against any substantial salt formation in these solids. In these complexes easier formation of ions may be apparent in the excited state, without much increasing the strength of the charge-transfer bonding in the ground state. The hypothesis seems worth considering that the

[17] Balk, Hoijtink, and Schrews, *Rec. Trav. chim.*, 1957, **76**, 813; Balk, de Bruijn, and Hoijtink, *ibid.*, p. 860.
[18] Wells, " Structural Inorganic Chemistry," Oxford Univ. Press, 1950, p. 70.

XUM

activation energies recorded refer to the energy required to convert a charge-transfer bond into an ion pair. This may be symbolised:

$$\underset{\text{Polarisation bond in ground state}}{Ar\sim\!\!\sim X} \longrightarrow \underset{\text{excited state}}{{}^{*}Ar^{+}\ X^{-}}$$

From such an activated ion pair electron-switching could easily occur to other molecules. The effect of benzanthrone as impurity on the conductance of the quinone [5] has not yet been studied with these complexes, which were all made from highly purified material. As already pointed out, for the solids, charge-transfer bonds may be formed between any one adduct molecule and more than one aromatic system in its immediate proximity. Although a formal 3-dimensional version of Mulliken's theory of charge-transfer bonds is not yet available, it can be seen in general terms how this kind of adduct formation in the solid can greatly increase the conductance. In particular, if thermal excitation at a charge-transfer bond leads to an actual separation of charges, the positive hole Ar^{+} or the extra electron of the anion X^{-} could then migrate separately in an applied electric field, leading to the observed electrical conductance.[19] From the sign of thermoelectric power of the isoviolanthrene–iodine complex (Table 2) electrons appear to be more mobile than holes, at any rate in this electron-acceptor adduct.

(iii) Electron-donor complexes between alkali-metal atoms and isoviolanthrene clearly exhibit much stronger interactions than are present in the electron-acceptor complexes, as is shown, for example, by the marked electrostriction in the solid adducts. Because of the near-stoicheiometric transfer of electrons on complex formation, π-electron systems of individual molecules are likely to undergo profound disturbances in these crystals. Electron-switching across adduct bridges from one aromatic molecule to another no longer seems a useful model to describe conduction in this instance, and a band system applying to the solid as a whole seems necessary to give even an approximate description of the conduction process. If the model of a salt-like lattice applies even approximately to this group of complexes, their high conductance compared with the insulator properties of a salt such as sodium chloride presumably arises from the overlap of electronic energies of the aromatic ions. Tables 2 and 3 show that the conductance increases as the proportion of alkali metal incorporated increases. This can almost certainly be attributed to increased band overlap.

Until detailed *X*-ray studies of the structures of the adducts can be made, it does not seem profitable to discuss their conductance mechanisms in much greater detail. Knowledge about structures of simpler polarisation-bond adducts, such as silver perchlorate–benzene [20] and benzene–bromine,[21] suggests a " sandwich " type of arrangement in which the foreign molecules lie underneath and probably slightly skew to the benzenoid planes. The direction of principal conductivity would be expeced to be largest normal to these planes, in the direction of the polarisation bonds. For this type of electrical conductance, when potassium is intercalated, or when crystalline compounds are formed with various electron-acceptors,[6] a limiting case appears to be presented by the electronic properties in the direction of the *c*-axis of the polynuclear layers in graphite. Further development of this electronic analogy between graphite and large aromatic molecules [22] presents some interesting possibilities.

One of us (N. D. P.) thanks the Shell Petroleum Company for a research maintenance grant.

Department of Chemical Engineering and Chemical Technology,
Imperial College of Science and Technology,
S. Kensington, London, S.W.7. [*Received, November 2nd*, 1960.]

[19] Martin and Ubbelohde, unpublished work.
[20] Rundle and Smith, *J. Amer. Chem. Soc.*, 1958, **80**, 5075.
[21] Hassel, *Mol. Phys.*, 1958, **1**, 241.
[22] Ubbelohde, *Nature*, 1933, **132**, 1002.

403. *Studies with Dithizone. Part IX.*[1] *The Absorption Spectra of Mono- and Di-*p*-bromo-substituted Dithizones and of their Metal Complexes.*

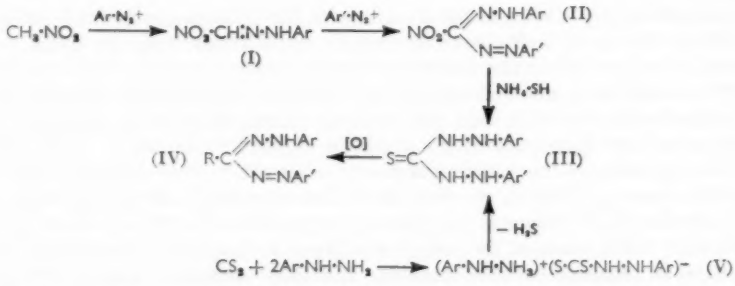
By H. Irving and R. S. Ramakrishna.

1(or 5)-*p*-Bromophenyl-3-mercapto-5(or 1)-phenylformazan ("monobromodithizone") has been synthesised and shown to be identical with the monobromination product of dithizone itself. 1,5-Di-(*p*-bromophenyl)-3-mercaptoformazan ("dibromodithizone") prepared by Fischer's method has been shown to be identical with the material prepared by two other synthetic routes. The absorption spectra of dithizone and of mono- and di-bromodithizone in benzene and carbon tetrachloride have been measured, and the molecular extinction coefficients of the pure reagents determined by the mercury titration method.

The pH range for complete extraction of a number of metal complexes of the three reagents have been determined and values are recorded for $\lambda_{max.}$ and $\varepsilon_{max.}$, the latter being obtained by a new reversion procedure. Values of $\lambda_{max.}$ increase in the order $Ag^{+} < Hg^{2+} \simeq Bi^{3+} < Pb^{2+} < Zn^{2+} < Cu^{2+}$, and those of $\varepsilon_{max.}$ in the order Ag < Cu < Pb < Hg < Bi < Zn. Substitution by bromine produces a regular bathochromic shift in values of $\lambda_{max.}$ for both the reagents and their metal complexes: the value for monobromodithizone is always the arithmetical mean of those for the unsubstituted and the dibromo-substituted reagent. There are no obvious regularities in values of $\varepsilon_{max.}$.

Discrepancies between the present extensive data and some results of Pupko and Pelkis are attributed to their use of impure materials.

"Dibromodithizone" (1,5-di-*p*-bromophenyl-3-mercaptoformazan) (as IV; R = SH, Ar = Ar′ = *p*-Br·C_6H_4) was first described by Hubbard and Scott [2] who prepared it by reducing the nitroformazan (as II) obtained by coupling nitromethane with *p*-bromobenzenediazonium chloride following the general method of Bamberger *et al.*[3] They described it as "insoluble in aqueous ammonia" and as possessing "low tinctorial power."



Authentic dibromodithizone was prepared by Irving and Bell [4] (*a*) by a modification of Bamberger's method,[3] and (*b*) by the action of sodium hydrogen sulphide upon 3-bromo-1,5-di-*p*-bromophenylformazan (as IV; R = Br, Ar = Ar′ = *p*-Br·C_6H_4). It was shown to resemble dithizone in all its reactions, to be soluble in aqueous ammonia, and to have the high molecular extinction coefficient of 30,600 at $\lambda_{max.}$ 635 mμ.

[1] Part VIII, Irving and Cox, *J.*, 1961, 1470.
[2] Hubbard and Scott, *J. Amer. Chem. Soc.*, 1943, **65**, 2390.
[3] Bamberger, Padova, and Ormerod, *Annalen*, 1925, **446**, 260.
[4] Irving and Bell, *J.*, 1953, 3538.

XUM

Dibromodithizone must also have been obtained by Beckett and Dyson [5] from thiocarbonyl chloride and *p*-bromophenylhydrazine hydrochloride. They describe its colour reaction with plumbous ions but give no details of the preparation or analysis.

More recently Pupko and Pel'kis [6,7] have reported the preparation of a very large number of analogues of dithizone (as IV; R = SH) both symmetrically (Ar = Ar') and unsymmetrically (Ar ≠ Ar') substituted. However, the values they give for molecular extinction coefficients (generally for solution in benzene) of the reagents are often very different from ours and those of other workers and for reasons given later they appear to be unreliable. For example, their data for molecular extinction coefficients in benzene of a sample of dibromodithizone prepared by Bamberger's method, and of a sample of dithizone itself (Table 1) differ so radically from values found in other solvents that a reinvestigation seemed desirable.

We have repeated the preparation of 1,5-di-*p*-bromophenyl-3-mercaptoformazan by Bamberger's method [3] and have also synthesised it by Fischer's method,[8] which involves oxidising the thiocarbazide (as III) obtained by heating the salt (V) that results from the interaction of carbon disulphide and *p*-bromophenylhydrazine. These two preparations were shown by infrared and visible absorption spectrophotometric measurements to be indistinguishable, and identical with the sample previously prepared [4] from the 3-bromoformazan (IV; R = Br, Ar = Ar' = *p*-Br·C_6H_4). Measurements of the absorption spectra of this " dibromodithizone " after rigorous purification are shown in Tables 3 and 4.

In a recent paper [9] we have shown that the bromination of dithizone yields an adduct of bromine with a monobrominated dithizone which was found to be 1(or 5)-*p*-bromophenyl-3-mercapto-5(or 1)-phenylformazan (as IV; R = SH, Ar = Ph, Ar' = *p*-Br·C_6H_4) by degradation and infrared measurements. We have now further confirmed its composition by comparison with an authentic specimen prepared by reducing the nitroformazan (II; Ar = Ph, Ar' = *p*-Br·C_6H_4) obtained by coupling nitroformaldehyde phenylhydrazone (I; Ar = Ph) with *p*-bromobenzenediazonium chloride at a controlled pH.

The preparation of the intermediate nitroformaldehyde phenylhydrazone (as I) proved troublesome. It is formed together with the nitroformazan (II; Ar = Ar') when benzenediazonium chloride is condensed with sodium *aci*-nitromethane under rigorously controlled conditions, but none of the published methods proved entirely satisfactory. Bamberger's first procedure [10] was later improved by his school [11] but Jensen and Bak [12] characterised this as " capricious " and described a modification in great detail. In our hands a mixture of products (I) and (II) invariably resulted and the proportion of nitroformazan increased with the time the nitroformaldehyde phenylhydrazone and the diazonium solution were allowed to react together. The instruction to wait for four hours before collecting the product [12] must have arisen from a mistranslation of " nach viertelstundigem Stehen . . . " in Bamberger's original paper. By using the procedure detailed in the experimental section we still obtained a mixture of products (I) and (II) but this could be readily separated by taking account of the greater acidity of the nitroformaldehyde phenylhydrazone. This substance was most conveniently purified after conversion of the crude mixture of α- and β-forms into the yellow β-form.

Samples of dithizone, monobromodithizone, and dibromodithizone were exhaustively purified by Cowling and Miller's method,[13] and their molecular extinction coefficients

[5] Beckett and Dyson, *J.*, 1937, 1358.
[6] Pupko and Pel'kis, *Zhur. obschei Khim.*, 1954, **24**, 1640.
[7] Pel'kis, Dubenko, and Pupko, *Zhur. obschei Khim.*, 1957, **27**, 2190.
[8] Fischer, *Annalen*, 1878, **180**, 120.
[9] Irving and Ramakrishna, *J.*, 1961, 1272.
[10] Bamberger, *Ber.*, 1894, **27**, 155.
[11] Bamberger, Schmidt, and Levinstein, *Ber.*, 1900, **33**, 2059.
[12] Jensen and Bak, *J. prakt. Chem.*, 1938, **151**, 167.
[13] Cowling and Miller, *Ind. Eng. Chem. Analyt.*, 1941, **13**, 145.

XUM

were obtained by the mercury titration procedure [4,14,15] after a preliminary study of the pH range over which quantitative extraction of the mercury complexes could be realised. Similar studies were then made of the pH range for complete extraction of complexes with the ions Ag^+, Hg^{2+}, Bi^{3+}, Pb^{2+}, Zn^{2+}, and Cu^{2+}. The molecular extinction coefficients of these complexes were then measured by a reversion procedure. If A^c is the absorbancy (measured at $\lambda_{max.}$ for the metal complex) of a solution obtained by equilibrating one of dithizone (HDz) of given known concentration in an organic solvent with an excess of an aqueous solution of an n-valent cation, and A_R^r is the absorbancy (measured at $\lambda_{max.}$ for the reagent itself) after this solution has been treated with a reagent that reverts the whole of the metal complex, MDz_n, quantitatively into the equivalent amount of dithizone, it can be shown [15] that:

$$A^c = A_R^r\,(\varepsilon_c^c + n\sum k_i\varepsilon_i^c)/(n\varepsilon_r^r + n\sum k_i\varepsilon_i^r) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The subscripts c, r, and i refer to metal complex, reagent, and any adventitious impurities respectively; k_i is the constant of proportionality; the superscripts c and r designate the wavelengths at which the complex and the reagent show their maximum absorption. The plot of A^c against A_R^r for reagent solutions of different initial concentrations is a straight line passing through the origin (Fig. 4). The value of $\varepsilon_c^c/n\varepsilon_r^r$ can be identified with the gradient provided the purity of the reagent used is greater than 95%; [15] this was the case for all the compounds studied in this paper. The value of ε_c^c for each metal complex follows from the value of ε_r^r previously determined.

Experimental

Preparation of 1,5-*Di*-p-*bromophenyl*-3-*mercaptoformazan* (IV; R = SH, Ar = Ar′ = *p*-Br·C_6H_4) [with G. F. Watts].—Carbon disulphide (8 g., excess) in a little ether was added slowly to a stirred suspension of *p*-bromophenylhydrazine (20 g.) in ether (50 ml.) and methanol (25 ml.). During 45 min. the *p*-bromophenylhydrazinium salt of β-(*p*-bromophenyl)dithiocarbazic acid separated as a white solid (21 g.), m. p. 95—96°. The salt was collected and a portion (16·7 g.) heated cautiously in an open dish at 100° during 20 min., with stirring. Hydrogen sulphide was evolved and the material became viscous and finally liquid. The dish was chilled in ice and the contents were triturated with ethanol; colourless di-(*p*-bromophenyl)-thiocarbazide crystallised. The thiocarbazide was then heated for 2—3 min. with potassium hydroxide (6 g.) in boiling methanol (60 ml.). The deep red solution was poured into 2N-sulphuric acid (500 ml.), stirred, and cooled at 0°. *Di*-(p-*bromophenyl*)*thiocarbazone* separated as a black powder which was washed free from acid by decantation, collected, and dried *in vacuo* [yield 5·2 g.; m. p. 150° (decomp.)]. For analysis it was taken up in ammonia prepared by isopiestic distillation,[16] and after the red solution had been extracted with several portions of chloroform the dibromodithizone was reprecipitated with ice-cold " isopiestic " hydrochloric acid. A portion was further purified by Cooper and Sullivan's procedure [14] (Found: N, 13·3; Br, 38·8. $C_{13}H_{10}Br_2N_4S$ requires N, 13·5; Br, 38·6%).

Preparation of Nitroformaldehyde Phenylhydrazone (with F. R. Hale).—Sodium hydroxide (16 g., 0·4 mole) was dissolved in a little water, and ethanol (200 ml.) was added. On addition of nitromethane (24·4 g., 0·4 mol.) a white precipitate of a sodium salt appeared. This was redissolved in ice-cold water (2 l.) and kept at or below 0° until required.

A vigorously stirred diazonium solution from aniline (37·2 g., 0·4 mole) in concentrated hydrochloric acid (120 ml.) and water (250 ml.) containing ice (300 g.) and sodium nitrite (29 g.) was quickly neutralised to litmus by rapid addition of ice-cold sodium hydroxide. The solution of the sodium salt of aci-nitromethane, previously prepared, was then added in one portion. The colour changed through yellow to red, and a red precipitate was formed. Stirring was continued for exactly 15 min. after the addition of the nitromethane, then the precipitate was collected and washed repeatedly with water until no trace of alkali or alkali salts remained.

[14] Cooper and Sullivan, *Analyt. Chem.*, 1951, **23**, 613.
[15] Irving and Ramakrishna, *Analyst*, 1960, **85**, 860.
[16] Irving and Cox, *Analyst*, 1958, **83**, 526.

The red product was dissolved in 2N-sodium hydroxide (500 ml.) at 0° and stirred. 3N-Hydrochloric acid was then added dropwise. No change appeared at first but later yellow streaks marked each addition of acid. As soon as the solution had acquired a permanent orange-yellow colour the red precipitate (mainly 3-nitro-1,5-diphenylformazan but containing some nitroformaldehyde phenylhydrazone) was collected and the filtrate (still at 0°) treated dropwise with acid until it was just acid to litmus. The yellow precipitate of β-nitroformaldehyde phenylhydrazone, collected and washed with water, had m. p. 83°. A further quantity was obtained from the initial red precipitate by repeating the fractional precipitation.

The yellow β-form could not be recrystallised readily and was converted into the red β-form by dissolution in warm chloroform and removal of the solvent in a current of air: this process was repeated three times. After recrystallisation from light petroleum (b. p. 40—60°) nitroformaldehyde phenylhydrazone formed orange-red needles (3·0 g.), m. p. 79—80°. Bamberger *et al.*[11] report m. p. 74·5—75·5°, and Jensen and Bak [12] m. p. 74° for samples heated rapidly from 70°. On slower heating there is partial conversion into the β-form.

FIG. 1. *Absorption spectra of complexes of silver and bismuth with dithizone* (*curve* 1, 3·180 × 10^{-5}M; *curve* 4, 1·135 × 10^{-5}M), *with monobromodithizone* (*curve* 2, 2·653 × 10^{-5}M, *curve* 5, 1·033 × 10^{-5}M), *and with dibromodithizone* (*curve* 3, 2·831 × 10^{-5}M; *curve* 6, 1·096 × 10^{-5}M).

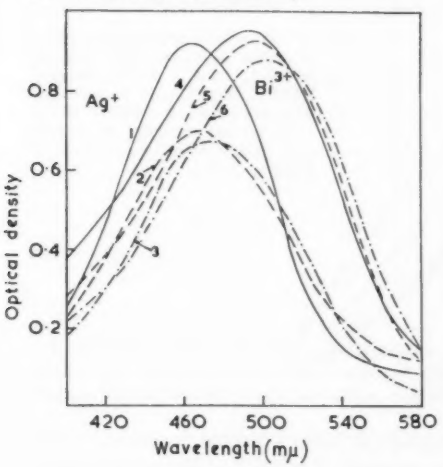
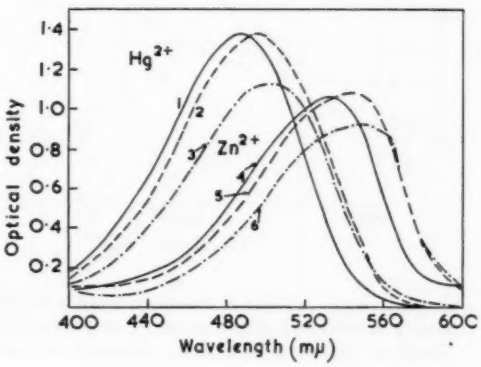


FIG. 2. *Absorption spectra of complexes of mercury and zinc with dithizone* (*curve* 1, 1·911 × 10^{-5}M; *curve* 4, 1·164 × 10^{-5}M), *with monobromodithizone* (*curve* 2, 1·820 × 10^{-5}M; *curve* 5, 1·146 × 10^{-5}M), *and with dibromodithizone* (*curve* 3, 1·580 × 10^{-5}M; *curve* 6, 1·048 × 10^{-5}M).



Preparation of 1(*or* 5)-p-*Bromophenyl*-3-*nitro*-5(*or* 1)-*phenylformazan*.—An ice-cold diazonium solution from *p*-bromoaniline (1·29 g., 3 mol.) in the minimum amount of hydrochloric acid was adjusted to pH 4—5 by the addition of solid sodium acetate and added to a vigorously stirred solution obtained by diluting a solution of the nitroformaldehyde phenylhydrazone (0·42 g., 1 mol.) in ethanol (5 ml.) to 700 ml. with water containing ice. After 20 min. the red precipitate of 1(or 5)-p-*bromophenyl*-3-*nitro*-5(or 1)-*phenylformazan* was collected, washed, and recrystallised from alcohol and then from chloroform–light petroleum, as a red microcrystalline powder, m. p. 164° (decomp.) (Found: N, 22·3; Br, 23·3. $C_{13}H_{10}BrN_5O_2$ requires N, 22·2; Br, 23·0%).

Preparation of 1(*or* 5)-p-*Bromophenyl*-3-*mercapto*-5(*or* 1)*phenylformazan*.—Dry ammonia was passed through a solution of the nitroformazan (1 g.) in ethanol (40 ml.) until it was saturated at 0°. Hydrogen sulphide was then passed through the (cooled) red solution until an orange colour developed (20 min.). Water was added and the precipitate of monobromodiphenylthiocarbazide was collected and washed. The crude thiocarbazide was then oxidised immediately with methanolic potassium hydroxide as described above. 1(or 5)-*p*-Bromophenyl-3-mercapto-5(or 1)-phenylformazan was finally obtained as a black microcrystalline powder, m. p. 152—153°, which was shown by its infrared and visible absorption spectra to be

XUM

identical with the substance obtained by the direct bromination of dithizone [9] (Found: Br, 23·6. Calc. for $C_{13}H_{11}BrN_4S$: Br, 23·8%).

Absorption Spectra.—(*a*) Salts of " AnalaR " quality were used for all solutions. Ammonia and hydrochloric acid were purified isopiestically.[16] Reagent-grade carbon tetrachloride was redistilled over lime immediately before use. Reagent-grade benzene was shaken with successive portions (15% v/v) of concentrated sulphuric acid until the acid layer remained colourless, then twice with 10% sodium carbonate solution, and once with water before being dried over calcium chloride and fractionated; the fraction of b. p. 79·5—80·5° was used.

The following metal solutions were used. Mercury: 2×10^{-3}M from mercuric chloride in 0·25N-sulphuric acid. Zinc: 2×10^{-2}M from zinc sulphate heptahydrate in 0·25N-sulphuric acid. Lead: 2×10^{-3}M from lead nitrate in 1% nitric acid. Copper: 2×10^{-3}M from copper sulphate pentahydrate in 0·25N-sulphuric acid. Silver: 3×10^{-3}M from silver nitrate in 0·25N-sulphuric acid. Bismuth: 4×10^{-3}M from bismuth nitrate pentahydrate in 1 : 100 nitric acid. Mixtures of sodium acetate and hydrochloric acid, acetic acid and sodium acetate, potassium dihydrogen phosphate and sodium hydroxide, and citric acid and aqueous ammonia were used as buffer solutions to cover the pH ranges 1—3, 2·4—5·9, 6·0—8·0, and 8·0—10

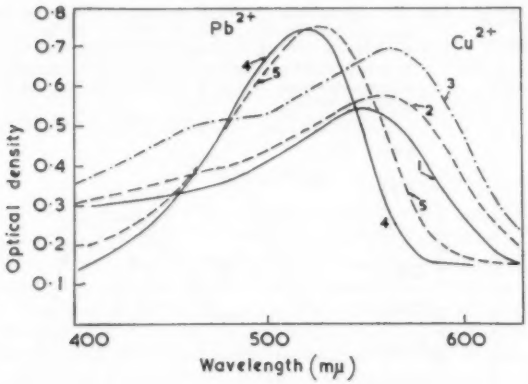


FIG. 3. *Absorption spectra of complexes of copper and lead with dithizone* (*curve* 1, $1{\cdot}211 \times 10^{-5}$M; *curve* 4, $1{\cdot}113 \times 10^{-5}$M), *with monobromodithizone* (*curve* 2, $1{\cdot}165 \times 10^{-5}$M; *curve* 5, $1{\cdot}081 \times 10^{-5}$M), *and copper with dibromodithizone* (*curve* 3, $1{\cdot}393 \times 10^{-5}$M).

respectively. All buffer solutions were extracted exhaustively with successive portions of a strong solution of dithizone in carbon tetrachloride to remove traces of metallic impurities. Residual dithizone was then removed by extraction with successive portions of carbon tetrachloride.

Dithizone and its analogues were purified by Cowling and Miller's method,[13] until no further changes in absorption spectra were detectable. An ammoniacal solution of the purest reagent was acidified with pure hydrochloric acid in the presence of the appropriate organic solvent into which it was immediately extracted. Such stock solutions (approx. 10^{-2}M) were stored in the dark under sulphur dioxide. Immediately before use they were further purified by a cycle of extractions into alkali [14] and diluted as required by pure solvent.

All glass-ware was scrupulously freed from traces of metals as previously described. Absorption spectra were obtained with a Unicam S.P. 700 recording spectrophotometer, but final measurements of absorbancy were made with a Unicam S.P. 500 spectrophotometer and matched 1 cm. silica cells.

(*b*) The purification of each reagent was continued until the peak ratio (the ratio of the optical densities at the maxima of longer and shorter wavelength) showed no further increase. Data recorded in this paper for reagents and their metal complexes refer only to solutions purified to this degree. Typical absorption spectra of dithizone and its mono- and di-bromo-substitution products have been presented previously.[9] The concentrations of such solutions were determined by the mercury titration procedure, and the calculated molecular extinction coefficients are summarised in Tables 3 (benzene) and 4 (carbon tetrachloride).

The absorption spectra of metal complexes were obtained by equilibrating solutions of the reagents in the desired solvents with an excess of metal ion dissolved in a buffer chosen from

preliminary experiments (see above) to lie within the range over which the complex is quantitatively extracted. Typical results are shown in Figs. 1—3. The locations of the maxima of the absorption bands are summarised in Table 5.

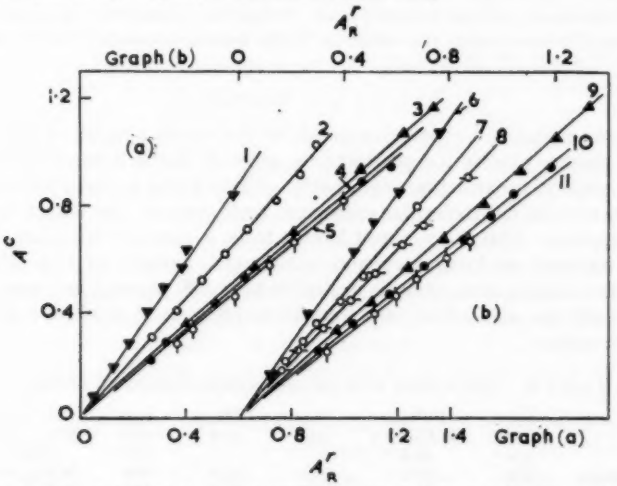
The pH range over which the metal complexes were best extracted was determined by measuring the absorbancy of the organic phase obtained by equilibrating a fixed volume of

TABLE 1. pH *ranges for maximum extraction of metal complexes of brominated dithizones.*

Metal	pH range for max. extraction	Buffer and pH
Hg^{2+}	1	H_2SO_4, 1
Ag^{+}	2—2·5	H_2SO_4, 2
Cu^{2+}	1·8—2·8	NaOAc–HCl, 2·6
Zn^{2+}	6·5—8·0	KH_2PO_4–NaOH, 7·40
Pb^{2+}	8·6	Citric acid–NH_3, 9·00
Bi^{3+}	9·0	NH_4 citrate–KCN, 9·60

stock reagent solution with an excess of metal ions dissolved in buffers whose pH was later measured. The pH range over which the absorbancy was constant or maximal was taken as

FIG. 4. *The reversion method for determination of molecular extinction coefficients of metal–dithizone complexes.* (a) *Complexes with* 1,5-*di*-p-*bromophenylthiocarbazone* (*lower scale*). (b) *Complexes with* 1(or 5)-p-*bromophenyl*-5(or 1)-*phenylthiocarbazone* (*upper scale*).



1 & 6, Zn^{2+}; 2 & 7, Hg^{2+}; 3 & 9, Bi^{3+}; 4 & 10, Ag^{+}; 5 & 11, Cu^{2+}; 8, Pb^{2+}.

the optimum pH range for extraction. These were found to be much the same for the brominated reagents as for dithizone itself (Table 1).

The molecular extinction coefficients of the various metal—dithizone complexes were

TABLE 2. *Gradients of lines obtained in the reversion method for measuring molecular extinction coefficients.*

	Hg^{2+}	Zn^{2+}	Cu^{2+}	Pb^{2+}	Ag^{+}	Bi^{3+}
Dithizone	1·044	1·329	0·650	0·961	0·812	0·815
Monobromodithizone	1·106	1·383	0·744	1·010	0·776	0·873
Dibromodithizone	1·139	1·431	0·792	—	0·766	0·853

determined by the reversion procedure as follows: x Ml. of dithizone solution ($3{\cdot}72 \times 10^{-5}$M) and ($10 - x$) ml. of carbon tetrachloride were equilibrated with 10 ml. of a solution of bismuth ions ($4{\cdot}459 \times 10^{-5}$M) and 10 ml. of an ammonium citrate–potassium cyanide buffer of pH

XUM

9·70 for 10 min. After centrifugation of the organic layer to remove any water droplets its absorbancy was measured at 490 mμ ($\lambda_{max.}$ for the bismuth complex) and at 620 mμ ($\lambda_{max.}$ for dithizone—to confirm the absence of residual reagent). 5 Ml. of the organic phase were then shaken with 5 ml. of 2N-sulphuric acid pre-saturated with carbon tetrachloride. The absorbancy of the organic phase was determined at 620 mμ (to obtain the value of A^r_R) and at 450 mμ (to give a value for the peak ratio of the reverted dithizone). Typical results are shown below with corresponding data for mono- and di-bromodithizone complexes of bismuth.

Initial concn. of reagent (10^5M)	Dithizone 3·72				Monobromodithizone 4·15				Dibromodithizone 4·35			
	A^e	A^r_R	A^e	A^r_R	A^e	A^r_R	A^e	A^r_R	A^e	A^r_R	A^e	A^r_R
Wavelength (mμ)	490	620	490	620	496	628	496	628	500	635	500	635
Absorbancy	0·889	1·089	0·510	0·620	1·175	1·333	0·678	0·786	1·152	1·340	0·693	0·820
	0·809	0·982	0·412	0·503	1·056	1·210	0·562	0·642	1·053	1·235	0·571	0·663
	0·714	0·861	0·324	0·388	0·930	1·018	0·438	0·505	0·925	1·073	0·470	0·538
	0·605	0·738	—	—	0·801	0·931	0·330	0·370	0·819	0·950	—	—

Similar measurements were carried out with other metals by using the following reversion agents. Mercury: A solution containing potassium hydrogen phthalate (25 g.) and potassium iodide (60 g.) in a litre of distilled water with a few drops of sodium thiosulphate solution to reduce any free iodine. Lead: N-hydrochloric acid. Copper: 0·5N-sodium thiosulphate. Silver: 6% (w/v) potassium iodide in 0·25N-sulphuric acid. Zinc: N-hydrochloric acid. The experimental results are plotted in Fig. 4. From the gradients of the best straight lines through the experimental points the values in Table 2 were calculated for the ratios $\epsilon^r_c/n\epsilon^r_r$.

Results and Discussion

The positions of the two absorption bands in the visible spectra of dithizone and its mono- and di-bromo-substitution products are given in Table 3 together with values for the respective molecular extinction coefficients. Table 3 also includes values for the peak ratios, *i.e.*, the ratio of the molecular extinction coefficients at the longer and the shorter wavelength maxima. This ratio is well known to be a sensitive criterion of purity since the common impurity in laboratory and commercial samples of thiocarbazones is an oxidation product whose absorption is negligible near 630 mμ and increases as the wavelength falls to 450 mμ and below: the immediate effect is to produce a decrease in the measured peak ratio.

Table 3. *Absorption data for mercaptoformazans in benzene.*

Reagent	$\lambda_{max.}$	$10^{-3}\epsilon_{max.}$	$\lambda_{min.}$	$10^{-3}\epsilon_{min.}$	$\lambda_{max.}$	$10^{-3}\epsilon_{max.}$	Peak ratio
Dithizone	450	20·6 ± 0·1	514	5·56	620	37·1 ± 0·2	1·80
	450 [b]	45·9 [b]			620 [b]	79·0 [b]	1·72 [b]
Monobromodithizone	456	20·1	520	5·79	626	36·9 ± 0·6	1·84
Dibromodithizone ...	464	22·4	527	7·19	635	40·9 ± 0·4	1·83
	454 [b]	19·0 [b]	—	—	638 [b]	23·0 [b]	1·21 [b]

[a] Value of ratio of $\epsilon_{max.}$ for the two absorption maxima. [b] Data from Pupko and Pel'kis (refs. 6, 7). All other data from the present paper. The extinction coefficients are mean values of two independent determinations on different samples.

Table 4. *Absorption data for mercaptoformazans in carbon tetrachloride.*

Reagent	$\lambda_{max.}$	$10^{-3}\epsilon_{max.}$	$\lambda_{min.}$	$10^{-3}\epsilon_{min.}$	$\lambda_{max.}$	$10^{-3}\epsilon_{max.}$	Peak ratio
Dithizone	450	20·3	515	5·48	620	34·6	1·70 [a]
	450	21·4	515	5·4	620	36·4	1·70 [b]
Monobromodithizone	458	21·0	520	5·84	628	34·5	1·64
Dibromodithizone ...	464	19·6	526	6·07	635	31·4	1·60

[a] Ref. 14. [b] Ref. 18.

While Pupko and Pel'kis's values of $\lambda_{max.}$ for dithizone are confirmed by ours, the values they give for dibromodithizone are substantially different. Their values for molecular extinction coefficients are in serious disagreement with ours and with those of

all other workers.[17,18] Values they have reported for each of a large number of other analogues of dithizone differ from the results of other workers to much the same extent. Pupko and Pel'kis state that all their measurements were made with solutions of the same concentration ($6{\cdot}6 \times 10^{-5}$ mole/l.). This appears to imply that these solutions had been prepared by weighing solid reagents: but their papers make no reference to any attempts to purify their crude preparations. If 1 cm. cells were used in their work, the stated concentration implies also that optical densities up to 4·0 were measured.

It is common knowledge that commercial samples of dithizone often show a purity of 85% or less based on mercurimetric titration and Cooper and Sullivan's values for the peak ratio of the purest known samples of dithizone. Several cycles of extraction by aqueous ammonia and reacidification in contact with a solvent are needed to bring the purity, as judged by the peak ratio, to its maximum value.[13,14,18] That Pupko and Pel'kis's sample of dithizone was impure follows from the low value they report for its peak ratio (Table 3), but no simple explanation can be put forward to explain why they found a value for $\varepsilon_{max.}$ more than twice as great as that found by any other worker in this field.[14,17,18] The very low peak ratio recorded for dibromodithizone shows that their sample was grossly impure: this conclusion is supported by the low values they record for the value of $\varepsilon_{max.}$ at 638 mμ.

Date for solutions in carbon tetrachloride are summarised in Table 4. In this solvent the intensities of absorption at the longer wavelength maxima are slightly lower than in benzene and values of peak ratios are uniformly lower. But the general similarity of data for the two solvents lends further weight to our criticisms of Pupko and Pel'kis's work.

From Tables 3 and 4 it is clear that the introduction of *p*-bromine atoms into diphenylthiocarbazone produces a bathochromic shift in the position of each of the prominent absorption bands in the visible region. The value of $\lambda_{max.}$ for monobromodithizone is the arithmetic mean of the values for dibromodithizone and dithizone itself. This confirms a generalisation made by Pupko and Pel'kis from a wider range of compounds which, as pointed out above, do not appear to be individually reliable. Pupko, Dubenko, and Pel'kis also stated (*a*) " that with the introduction of electron-acceptor substituents in the phenyl groups of dithizone the molar coefficient of extinction is decreased, the latter having a value several times less than that of dithizone " and (*b*) " when haloids are introduced into the phenyl groups of 1,5-diphenylthiocarbazones the intensity of the long-wave maximum is decreased with a simultaneous increase in the intensity of the short-wave maximum." [7] The present data provide no support for such generalisations.

TABLE 5. *Absorption spectra of various metal complexes of* 3-*mercaptoformazans in carbon tetrachloride.*

Metal		Ag^+	Hg^{2+}	Bi^{3+}	Pb^{2+}	Zn^{2+}	Cu^{2+}
Dithizone	$\lambda_{max.}$ (mμ)	462	490	490	520	536	548
	$10^{-3}\varepsilon_{max.}$	29·1	72·2	84·6	66·5 [a]	92·0 [a]	45·0 [a]
Monobromodithizone	$\lambda_{max.}$ (mμ)	468	496	496	526	544	558
	$10^{-3}\varepsilon_{max.}$	26·7 [a]	76·1	90·0	69·4	95·1	49·6
Dibromodithizone	$\lambda_{max.}$ (mμ)	472	502	500	—	552	566
	$10^{-3}\varepsilon_{max.}$	24·0	71·5	80·3	—	89·7	49·7

[a] Data from ref. 17.

From values of the ratio $\varepsilon_c^c/n\varepsilon_r^c$ from Table 2 and the values of ε_r^c given in Table 4 it was possible to calculate values for the molecular extinction coefficients of various metal–dithizone complexes. These are summarised in Table 5 together with the position of the maximum of the prominent absorption band. For each reagent it was found that $\lambda_{max.}$ increased in the order $Ag^+ < Hg^{2+} \approx Bi^{3+} < Pb^{2+} < Zn^{2+} < Cu^{2+}$. There is again a

[17] Iwantscheff, " Das Dithizon und seine Anwendung in der Mikro- and Spurenanalyse," Verlag Chemie, Weinheim, 1958.
[18] Weber and Vouk, *Analyst*, 1960, **85**, 40.

bathochromic shift for each metal caused by bromine-substitution, and the value of $\lambda_{max.}$ for the complex of any metal with monobromodithizone is the arithmetic mean of the values for the dibromodithizone and dithizone complex. Values of $\epsilon_{max.}$ increase in the order Ag < Cu < Pb < Hg < Bi < Zn for each reagent, but there is no systematic trend in individual values as a result of bromine substitution in the parent reagent.

The brominated dithizones appeared to be more soluble than dithizone in aqueous alkali, pointing to a higher acidity of the thiol grouping. The complex of lead with dibromodithizone and of cadmium with either mono- or di-bromodithizone formed red and orange flocks respectively, almost insoluble in carbon tetrachloride. Saturated organic solutions of these metal complexes decomposed too rapidly to permit accurate measurements of their absorption spectra.

We are indebted to the Royal Society for the loan of a recording spectrophotometer (S.P. 700). One of us (R. S. R.) gratefully acknowledges facilities for study leave provided by the Council of the University of Ceylon.

INORGANIC CHEMISTRY LABORATORY,
SOUTH PARKS ROAD, OXFORD.

[*Received, November 21st,* 1960.]

---

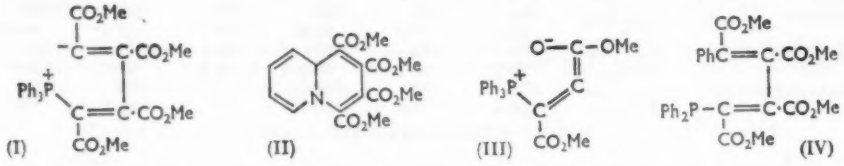
404. *The Adducts from Triphenylphosphine and Dimethyl Acetylenedicarboxylate.*

By A. W. JOHNSON and J. C. TEBBY.

Various adducts from dimethyl acetylenedicarboxylate and triphenylphosphine have been characterised and structures for these and certain rearrangement products are suggested.

As an extension of our studies of the reaction of dimethyl acetylenedicarboxylate with various pyridines,[1] we have examined the corresponding reaction of the acetylenic ester with triphenylphosphine which is known to react easily with many unsaturated compounds.[2] In the reaction of triphenylphosphine and acetylenic esters the formation of bicyclic systems, as observed with the pyridine, is not possible but several new types of adduct have been recognised. Corresponding compounds have not been obtained from triphenylamine or triphenylarsine.

When triphenylphosphine was treated with dimethyl acetylenedicarboxylate in dry ether at −50° in an atmosphere of nitrogen there was formed a yellow unstable adduct, the analysis of which indicated that each molecule of triphenylphosphine had reacted with two of the acetylenic ester. At room temperature in air, the adduct became brown fairly



rapidly but without loss of weight. By extraction with methanol the rearrangement product gave a second yellow solid which was extremely stable and was isomeric with its progenitor. Treatment of the unstable adduct with water, methanol, methyl iodide, or β-picoline also gave the stable isomer, and the first-formed adduct has therefore been provisionally formulated as the zwitterion (I). It will be recalled that Diels [3] assigned a

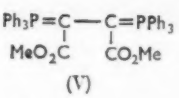
[1] Jackman, Johnson, and Tebby, *J.*, 1960, 1579.
[2] Horner and Hoffmann, *Angew. Chem.*, 1956, **68**, 473.
[3] Diels, Alder, Kashimoto, Friedrichsen, Eckardt, and Klare, *Annalen*, 1932, **498**, 16.

XUM

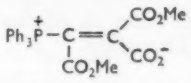
similar structure to the first-formed adducts from pyridine and dimethyl acetylenedicarboxylate, but these compounds, which are much more stable than would be expected of a zwitterionic structure, recently have been reformulated [1,4] as the 9a(*H*)-quinolizines (*e.g.*, II). Horner and Hoffmann [2] have assigned a structure analogous to (I) to an adduct obtained from the reaction of triethylphosphine and dimethyl acetylenedicarboxylate, but no details of the properties or preparation of the adduct were disclosed. On the other hand, they suggested (III) as the structure of an adduct they obtained from triphenylphosphine and the acetylenic ester. We have not observed the formation of a 1 : 1 adduct (as in III) except in combination with carbon dioxide (see below, VI) and it is of interest that the decomposition products, dimethyl fumarate and triphenylphosphine oxide, of their adduct (III) with water correspond to those of our adduct (VI).

The structure (IV) was deduced for the stable yellow rearrangement product from the results of oxidation with hydrogen peroxide in acetic acid, which gave diphenylphosphinic and benzoic acid. The rearrangement of (I) to (IV) is thus formally analogous to the Stevens rearrangement,[5] but instead of the usual 1,2-shift, the present example is a 1,5-shift which is doubtless facilitated by the proximity of the charged centres.* Moreover, this appears to be the first example of this type of rearrangement involving phosphonium salts [6] and one of the few examples involving the migration of a phenyl group.[7] A third product from the oxidation appeared to be a lactone derived from the aliphatic chain but the low yield precluded complete identification of this substance.

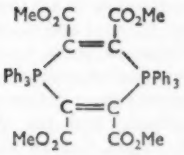
The stable adduct (IV) was obtained directly from triphenylphosphine and dimethyl acetylenedicarboxylate when they reacted in boiling ether and this was the best method of preparation. It was noted during these preparations that after the addition of



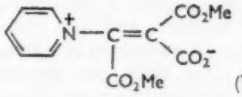
(V)



(VI)

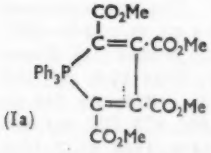


(VII)



(VIII)

0·5 mol. of the acetylenic ester to the triphenylphosphine, a thick yellow slurry was obtained which became less viscous as more acetylenic ester was added. This solid product was separated but it proved difficult to remove from it the small quantity of the adduct (IV) that was already present. Although satisfactory analyses were not obtained it appeared that this product is formed by the combination of two molecules of triphenylphosphine with each molecule of the acetylenic ester and accordingly (V) is suggested as a tentative structure. This product was decomposed rapidly by alcohols, yielding free



(Ia)

* We prefer to represent our adduct as having the charged structure (I), rather than the covalent structure (Ia), in order to provide a driving force for the migration of the phenyl group although we appreciate, as was pointed out by a Referee, that the rearrangement of (Ia) to (IV) would involve only a 1,2-shift.

[4] Acheson and Taylor, *J.*, 1960, 1691.
[5] Stevens, *J.*, 1930, 2107 and later papers; Kantor and Hauser, *J. Amer. Chem. Soc.*, 1951, **73**, 4122.
[6] Cf. Wittig *et al.*, *Annalen*, 1953, **580**, 57; 1955, **594**, 1.
[7] Cf. Wittig and Stahnecker, *Annalen*, 1957, **605**, 69.

triphenylphosphine and a small quantity of the stable adduct (IV). Although compound (V) was stable in air at room temperature it could not be sublimed.

When triphenylphosphine reacted with dimethyl acetylenedicarboxylate in dry ether at −50° in an atmosphere of carbon dioxide, another pale yellow unstable adduct was obtained. This compound evolved carbon dioxide at 50° and yielded a very stable orange-coloured product. In view of the method of preparation and the analytical figures it is suggested that this unstable adduct is the zwitterion (VI), *i.e.*, the first-formed zwitterion obtained by reaction of equimolecular quantities of the reagents is stabilised by combination with carbon dioxide to give the internal salt of a half-ester of a malonic acid.

Treatment of this, second zwitterion with water caused the formation of triphenylphosphine oxide and dimethyl fumarate, a reaction which emphasises the relation of (VI) to the Wittig reagents.[8] However, most other reagents, *e.g.*, methyl iodide, β-picoline, and dimethyl acetylenedicarboxylate, caused the rearrangement of (VI) to the stable orange adduct which has been formulated as (VII). Because of its insolubility in suitable solvents and its lack of volatility an accurate determination of the molecular weight of this adduct has not been carried out, but oxidation with hydrogen peroxide in acetic acid gave triphenylphosphine oxide together with a small quantity of an unidentified aliphatic ester.

Compounds apparently analogous to (VI) were encountered in the study of the adducts of dimethyl acetylenedicarboxylate and tripropylphosphine as well as the pyridine bases,[1] where, however, the decomposition occurred at room temperature. These adducts are now formulated as (VIII), the carbon dioxide necessary for their formation having been derived from the surrounding acetone–carbon dioxide cooling bath! In this series, as nitrogen cannot assume the quinquecovalent state, the decomposition with liberation of carbon dioxide takes an alternative course and free pyridine is liberated together with some dimethyl fumarate.

Experimental

Ultraviolet absorption spectra refer to ethanolic solutions except where otherwise stated.

Reaction of Triphenylphosphine and Dimethyl Acetylenedicarboxylate in a Nitrogen Atmosphere at −50°.—Triphenylphosphine (1 g.) was dissolved in dry ether (25 c.c.) and placed in a specially constructed flask designed so that all operations, including filtration, could be conducted in an atmosphere of nitrogen, and then cooled to −50°. Dimethyl acetylenedicarboxylate (0·8 g.) in dry ether (5 c.c.) was added in a thin stream and after a short time a yellow solid separated. After 10 min., the flask was removed from the cooling-bath, and the yellow solid (I) was separated and dried *in vacuo* (Found: C, 66·4; H, 5·15. $C_{30}H_{27}O_6P$ requires C, 66·0; H, 5·0%), $\nu_{max.}$ (KBr disc) 695, 721, 751, 772, 793, 997, 1050, 1100, 1180, 1245, 1320, 1385, 1435, 1480, 1535, 1585, 1640, 1655, 1690, 1740, 1890, 1970, 2900, and 3400 cm.$^{-1}$. The ultraviolet absorption was not determined because of the insolubility of the sample in suitable solvents. This *product* was unstable and readily decomposed even at room temperature to the stable yellow adduct (see below), either in the dry state or in acetone or ethanolic solution.

Reaction of Triphenylphosphine and Dimethyl Acetylenedicarboxylate in Boiling Ether.—Triphenylphosphine (10 g.) in dry ether (50 c.c.) was added gradually to dimethyl acetylenedicarboxylate (10·6 g.) in dry ether (100 c.c.). The mixture was heated under reflux for 1 hr., then cooled, and the resulting solid was separated. After being washed with ether, it was air-dried and formed a yellow-brown powder (19·2 g.), m. p. 180—220°. This was boiled with methanol (250 c.c.) for 3 hr., the hot solution filtered, and the residue (6·4 g.), m. p. 248—250°, recrystallised by Soxhlet extraction from a thimble with methanol. The *product* (III) formed small yellow prisms, m. p. 253—255° (Found: C, 65·7; H, 5·0; P, 5·5; OMe 22·3; *M*, 520. $C_{30}H_{27}O_6P$ requires C, 66·0; H, 5·0; P, 5·7; OMe, 22·7; *M*, 547), $\lambda_{max.}$ 228 and 344 mμ (log ε 4·44 and 4·32 respectively), $\nu_{max.}$ 698, 721, 728, 747, 757, 778, 791, 866, 873, 902, 944, 968, 1019, 1042, 1089, 1112, 1138, 1190, 1218, 1255, 1321, 1396, 1440, 1449, 1484, 1496, 1533, 1589, 1665, 1698, 1715, 1746, 2850, 2945, 2990, and 3060 cm.$^{-1}$. The adduct was soluble in chloroform or dioxan, slightly soluble in acetone or alcohol and insoluble in water or light petroleum.

[8] Trippett, "Advances in Organic Chemistry," Interscience, New York, 1960, Vol. I, p. 83.

The same stable adduct (0·6 g.) was obtained by keeping an ethereal solution of the above unstable adduct (I) (0·9 g.) at room temperature for 2 days. This transformation could also be achieved by heating the dry unstable adduct on the steam-bath or by treating it with water or with methyl iodide.

Oxidation of the Stable Yellow Triphenylphosphine Adduct.—The stable yellow adduct (8·5 g.) was heated with hydrogen peroxide (50 c.c.; 100-vol.) and glacial acetic acid (100 c.c.) on the steam-bath for 45 min. The whole was evaporated to dryness under reduced pressure, and acetone (20 c.c.) added to the residue. After cooling (refrigerator), the crystals of diphenylphosphinic acid [9] (1·6 g.) were separated, washed, and dried; they had m. p. and mixed m. p. 190—192°. The solvent was removed from the mother-liquors and the residue treated with methanolic 10% potassium hydroxide (20 c.c.). After the vigorous reaction had subsided, a further quantity of the reagent was added and the mixture heated under reflux for 1 hr. The methanol was distilled off and the residue treated with water (70—80 c.c.) and washed with chloroform (2 × 30 c.c.). The aqueous layer was acidified with concentrated hydrochloric acid and again extracted with chloroform (2 × 30 c.c.). This chloroform extract was washed and dried and then, after removal of the solvent, the cream-coloured solid residue was sublimed at 0·2 mm. and the crude sublimate (0·45 g.) extracted with hot water, to give benzoic acid (0·17 g.), m. p. 115°, raised to 121° after crystallisation, the identity of which was confirmed by its infrared spectrum. A further quantity of diphenylphosphinic acid (0·6 g.), m. p. 190—192°, was obtained by crystallisation from methanol of the sublimation residue; it had $\lambda_{max.}$ 224, 260, 265, and 270 mμ (log ε 4·15, 3·02, 3·11, and 2·91 respectively), $\lambda_{infl.}$ 295 mμ (log ε 2·25), $\nu_{max.}$ (KBr disc) 699, 703, 732, 760, 792, 867, 937, 968, 980, 1007, 1033, 1073, 1127, 1136, 1158, 1186, 1192, 1318, 1440, 1487, 1593, 1710, 3057, 3075, and 3583 cm.$^{-1}$.

Reaction of Triphenylphosphine and Dimethyl Acetylenedicarboxylate in a Carbon Dioxide Atmosphere at −50°.—Triphenylphosphine (1·5 g.) was dissolved in dry ether (30 c.c.) and cooled to −50°. Carbon dioxide was bubbled through the solution while dimethyl acetylenedicarboxylate (1 g.) in dry ether (5 c.c.) was added dropwise. The mixture was allowed to warm to room temperature and after 10 min. the colourless solid (V) (2·4 g.) was separated in an atmosphere of carbon dioxide, and washed with dry ether; it then had m. p. 78—80° (Found: C, 66·9; H, 5·1; P, 6·9. $C_{25}H_{21}O_6P$ requires C, 66·9; H, 4·7; P, 6·9%), $\nu_{max.}$ (KBr disc) 698, 724, 750, 757, 778, 862, 886, 925, 990, 1010, 1020, 1065, 1120, 1160, 1185, 1225, 1255, 1305, 1385, 1435, 1475, 1585, 1640, 1720, 2325, 2930, 3000, and 3400 cm.$^{-1}$. The ultraviolet absorption was not determined because of the instability of this *adduct* in solution. The solid evolved carbon dioxide rapidly at 50°; in a quantitative experiment 1 equiv. of carbon dioxide was evolved when the dry adduct was heated at 100° for ½ hr. At room temperature the adduct could be preserved for one day in a desiccator.

This adduct (7·7 g.) was shaken with cold water (80 c.c.) and after 1 hr. colourless crystals had separated. After cooling, these were removed and dried. When the product (5·8 g.) was purified by sublimation, dimethyl fumarate (1·1 g.), m. p. 102—104°, was obtained as the sublimate and after crystallisation of the residue (4·6 g.) from aqueous ethanol, triphenylphosphine oxide (3·2 g.), m. p. and mixed m. p. 155—156°, was also isolated.

Preparation of the Stable Orange Adduct (VI).—Dimethyl acetylenedicarboxylate (3·5 g.) in ether (10 c.c.) was added to a solution of triphenylphosphine (5 g.) in dry ether (70 c.c.) cooled to −50° while a slow stream of carbon dioxide was bubbled through the solution. After 10 min. the solid product was separated, added to methyl iodide (20 c.c.), and heated under reflux for 30 min. The resulting solid (4·5 g.) was again separated, washed with methanol, and dried in air. Purification was effected by a preliminary extraction with boiling acetone (70 c.c.) for 2 hr. to remove impurities, and then by crystallisation of the residue (4·05 g.; m. p. 246—247°) by Soxhlet extraction with chloroform which gave small orange rods (2·25 g.), m. p. 266° (Found: C, 70·2; H, 5·3; P, 7·6; Loss on drying, 1·4. $C_{48}H_{42}O_8P_2,\frac{1}{2}H_2O$ requires C, 70·5; H, 5·3; P, 7·6; H_2O, 1·1%), $\lambda_{max.}$ (in $CHCl_3$) 337 and 435 mμ (log ε 3·6 and 3·6), $\nu_{max.}$ (KBr disc) 701, 724, 748, 762, 767, 792, 809, 901, 913, 943, 1006, 1030, 1082, 1106, 1114, 1167, 1206, 1235, 1278, 1319, 1362, 1442, 1489, 1517, 1572, 1590, 1707, 2840, 2902, 2946, 2993, 3020, 3063, and 3085 cm.$^{-1}$. This *adduct* was insoluble in light petroleum, ether, water, methanol, and acetone, and was slightly soluble in chloroform and dioxan.

Oxidation of the Stable Orange Adduct (VI).—The adduct (1 g.) was mixed with hydrogen

[9] Michaelis and Götter, *Ber.*, 1878, **11**, 885.

XUM

peroxide (5 c.c.; 100-vol.) and glacial acetic acid (10 c.c.) and heated for 15 min. on the steam-bath. The product was evaporated to dryness and then heated at 100° under reduced pressure (water pump) to remove the last traces of solvent. The residue (0·6 g.) slowly crystallised and, by further sublimation or chromatography on an alumina column, pure triphenylphosphine oxide, m. p. and mixed m. p. 155—156°, was obtained. The infrared spectrum was identical with that of an authentic specimen.

We thank the Glaxo Triangle Trust for financial support (to J. C. T.) and Messrs. Albright and Wilson for the gift of certain phosphorus intermediates.

THE UNIVERSITY, NOTTINGHAM. [*Received, November 28th*, 1960.]

---

405. *The Use, in Wittig Reactions, of Phosphonium Salts and Phosphobetaines containing a Basic Group.*

By S. TRIPPETT and D. M. WALKER.

Quaternary phosphonium salts and phosphobetaines containing the *p*-dimethylaminophenyl group have been prepared and used in the Wittig olefin synthesis. The solubility of the resulting phosphine oxide in dilute acid facilitates the isolation of the resulting olefin.

ONE of the chief technical difficulties associated with the Wittig olefin synthesis is separation of the olefin from the accompanying phosphine oxide. When a phosphonium halide is used in ether with an alkyl- or aryl-lithium as base, most of the phosphine oxide can be removed as an insoluble complex with lithium halide, but in other solvents, *e.g.*, tetrahydrofuran, this is not possible. The problem becomes particularly acute when stable Wittig reagents such as formylmethylenetriphenylphosphorane are used.[1] A way of overcoming the difficulty appeared to be the incorporation in the phosphonium salt or phosphobetaine of a basic group which would allow ready separation of the resulting phosphine oxide by extraction into dilute acid. Such phosphonium salts and phosphobetaines have now been prepared and used in Wittig reactions with the expected benefits in the ease of isolation of the resulting olefins.

p-Dimethylaminophenyldiphenylphosphine was prepared by the action of phenylmagnesium bromide on *p*-dimethylaminophenyldichlorophosphine. Michaelis and Schenk [2] reported that, although this phosphine reacted vigorously with alkyl and benzyl halides, the resulting salts were not crystalline. This is true of the methiodide, but in general the salts with other alkyl and with benzyl halides are crystalline. The benzylphosphonium bromide with butyl-lithium and fluorenone gave benzylidenefluorene (75%). The phosphobetaines $p\text{-Me}_2\text{N}\cdot\text{C}_6\text{H}_4\cdot\text{PPh}_2{:}\text{CH}\cdot\text{COR}$ (I; R = H, Me, OEt, or Ph) were also prepared and used in Wittig reactions with aldehydes, the ease of isolation of the products being particularly striking (see Experimental section). The phosphonium salt from chloroacetaldehyde was exceptional in showing no infrared carbonyl absorption below 6·1 μ; this may mean that the salt is really an ammonium-phosphobetaine (the phosphobetaines show their carbonyl absorption [3] at 6·1 μ), but attempts to use it directly in Wittig reactions were unsuccessful. The aldehyde-betaine (I; R = H) with 2,7-dimethylocta-2,6-dien-4-yne-1,8-dial gave only 12% of the required C_{12}-dial, a yield comparable with that obtained by use of formylmethylenetriphenylphosphorane followed by counter-current distribution.[3] The low yields are not due to further reaction of the product with the betaines, as the C_{12}-dial does not react with phosphobetaines.

The non-crystalline methiodide from *p*-dimethylaminophenyldiphenylphosphine gave,

[1] Trippett and Walker, *Chem. and Ind.*, 1960, 202.
[2] Michaelis and Schenk, *Ber.*, 1888, **21**, 1497; *Annalen*, 1890, **260**, 1.
[3] Trippett and Walker, *J.*, 1961, 1266.

on alkaline hydrolysis, 82% of (*p*-dimethylaminophenyl)methylphenylphosphine oxide and is therefore substantially pure, but it could not be used successfully in Wittig reactions. Reduction of this phosphine oxide with lithium aluminium hydride gave (*p*-dimethylaminophenyl)methylphenylphosphine, which gave a crystalline methiodide. With butyllithium in tetrahydrofuran this methiodide gave a clear yellow solution which, on addition of *p*-nitrobenzophenone, became black: none of the expected olefin could be isolated. A similar failure in the use of a phosphonium iodide in a Wittig reaction has been reported,[4] but in that case—methylenetriphenylphosphorane and cyclopentanone—the reaction was normal when the bromide was used; in our case, use of the methobromide was equally unsuccessful, the clear yellow solution of phosphorane again becoming black on addition of *p*-nitrobenzophenone. This failure must be due to the nitro-group, for a similar reaction with benzophenone gave 1,1-diphenylethylene in 85% yield. Nitro-groups have not previously been found to interfere with Wittig reactions.

p-Dimethylaminophenyldichlorophosphine with methylmagnesium iodide gave *p*-dimethylaminophenyldimethylphosphine. The salts from this and benzyl bromide and phenacyl bromide were prepared and used in Wittig reactions. The phosphorane prepared from the methiodide again failed to react normally with *p*-nitrobenzophenone.

Experimental

p-*Dimethylaminophenyldiphenylphosphine*.—To a stirred solution of phenylmagnesium bromide, prepared from magnesium (13·6 g.) and bromobenzene (93 g.) in ether (250 ml.), cooled in ice–salt, was added *p*-dimethylaminophenyldichlorophosphine (42 g.) in ether (250 ml.) during 2 hr. The solution was stirred at room temperature for 1 hr. and cooled in ice, and saturated aqueous ammonium chloride (300 ml.) was added. The resulting precipitate was extracted into benzene (1·5 l.), the extract dried and evaporated to low bulk and ethanol (50 ml.) added. Crystallisation gave *p*-dimethylaminophenyldiphenylphosphine (42 g.), m. p. 152—153°.

Quaternisation with the following halides gave the corresponding phosphonium halides. *Ethyl bromide*, m. p. (from acetone–light petroleum) 193—194° (Found: C, 63·9; H, 6·1; N, 3·2. $C_{22}H_{25}BrNP$ requires C, 63·7; H, 6·1; N, 3·4%); *allyl bromide*, m. p. (from water) 232—234° (Found: C, 64·8; H, 5·85; N, 3·2. $C_{23}H_{25}BrNP$ requires C, 64·8; H, 5·9; N, 3·3%); *benzyl bromide*, m. p. (from chloroform–ethyl acetate) 227—228° (Found: N, 2·8. $C_{27}H_{27}BrNP$ requires N, 2·95%); *acetonyl chloride*, m. p. (from chloroform–ethyl acetate) 204—206° (Found: N, 3·5. $C_{23}H_{25}ClNOP$ requires N, 3·5%); *formylmethyl chloride*, m. p. (from chloroform–ethyl acetate) 172—173° (Found: N, 3·5. $C_{23}H_{23}ClNOP$ requires N, 3·65%); *ethoxycarbonylmethyl bromide*, m. p. 84—87° (Found: C, 58·7; H, 5·85; N, 2·7. $C_{24}H_{27}BrNO_2P,H_2O$ requires C, 58·7; H, 5·9; N, 2·75%). The salts from phenacyl bromide, chloroacetamide, and bromoacetamide were not crystalline.

Reaction of Benzylidene-(p-*dimethylaminophenyl*)*diphenylphosphorane with Fluorenone*.—To a stirred suspension of benzyl-(*p*-dimethylaminophenyl)diphenylphosphonium bromide (4·8 g.) in ether (100 ml.), ethereal 1·3N-butyl-lithium (8·5 ml.) was added, followed after 10 min. by fluorenone (1·85 g.) in ether (25 ml.). The resulting suspension was set aside at room temperature for 18 hr., then washed with dilute hydrochloric acid and with water, dried, and evaporated. Crystallisation of the residue from ethanol gave 9-benzylidenefluorene (75%), m. p. 72—74°, undepressed on mixture with an authentic sample of m. p. 74—75°.

A similar reaction with benzyl-(*p*-dimethylaminophenyl)dimethylphosphonium bromide gave a 78% yield of benzylidenefluorene.

Acetonylidene-(p-*dimethylaminophenyl*)*diphenylphosphorane*.—Acetonyl-(*p*-dimethylaminophenyl)diphenylphosphonium chloride (4·5 g.) was dissolved in water (100 ml.) at 0°, and the solution was made alkaline to phenolphthalein with dilute sodium hydroxide, and extracted with chloroform. The extract was dried and evaporated. Crystallisation of the residue from ethyl acetate gave the *phosphorane*, m. p. 176—177° (Found: N, 4·1. $C_{23}H_{24}NOP$ requires N, 3·9%).

[4] Collins and Hammond, *J. Org. Chem.*, 1960, **25**, 1435.

XUM

A solution of this phosphorane (2·5 g.) and benzaldehyde (0·75 g.) in benzene (50 ml.) was refluxed for 7 hr., cooled, and washed with dilute hydrochloric acid (3 times) and with water. Evaporation, and crystallisation of the residue from light petroleum (b. p. 40—60°) at 0°, gave benzylideneacetone (78%), m. p. 40—41° (lit., m. p. 42°).

Formylmethylene - (p - *dimethylaminophenyl*)*diphenylphosphorane*.—Formylmethyl - (*p* - dimethylaminophenyl)diphenylphosphonium chloride was dissolved in ethanol, triethylamine (1·1 mol.) added, and the solution diluted with much water and extracted with benzene. The extract was dried and evaporated to give the *phosphorane*, m. p. (from acetone) 210—211° (Found: C, 75·9; H, 6·5; N, 4·1. $C_{22}H_{22}NOP$ requires C, 76·1; H, 6·65; N, 4·0%).

A solution of this phosphorane (1·5 g.) and 2,7-dimethylocta-2,6-dien-4-yne-1,8-dial (0·32 g.) in benzene (30 ml.) was refluxed for 19 hr., cooled, washed with dilute hydrochloric acid and with water, dried, and evaporated. Crystallisation of the residue from aqueous methanol gave 4,9-dimethyldodeca-2,4,8,10-tetraen-6-yne-1,12-dial (12%), m. p. and mixed m. p. 161—162°. A similar reaction with benzaldehyde gave cinnamaldehyde, isolated as the 2,4-dinitrophenylhydrazone (58%), m. p. and mixed m. p. 252—253°.

Ethoxycarbonylmethylene-(p-*dimethylaminophenyl*)*diphenylphosphorane*.—A solution of ethoxycarbonylmethyl-(*p*-dimethylaminophenyl)diphenylphosphonium bromide (1 g.) in ethanol (15 ml.) at 0° was made alkaline to phenolphthalein with dilute sodium hydroxide solution, diluted with ice-water, and rapidly extracted with chloroform. The extract was dried and evaporated, and the residue crystallised from ethyl acetate–light petroleum to give the *ester-phosphorane* (0·8 g.), m. p. 141—142° (Found: C, 73·9; H, 6·65; N, 3·55. $C_{24}H_{26}NO_2P$ requires C, 73·7; H, 6·65; N, 3·6%).

A solution of this phosphorane (2·3 g.) and benzaldehyde (0·6 g.) in benzene (50 ml.) was refluxed for 18 hr., cooled, washed with dilute hydrochloric acid and with water, dried, and evaporated. The residue, after hydrolysis with alcoholic 2N-sodium hydroxide for 0·5 hr., gave, on acidification, cinnamic acid (0·7 g.), m. p. and mixed m. p. 132—133°.

(p-*Dimethylaminophenyl*)*dimethylphenylphosphonium Bromide*.—Finely powdered (*p*-dimethylaminophenyl)methylphenylphosphine oxide (14 g.) was added in 15 min. to a stirred solution of lithium aluminium hydride (6 g.) in dibutyl ether (150 ml.) heated on a water-bath. Heating was continued for 18 hr., the suspension was cooled, methanol (30 ml.) was added, and solvents were removed under reduced pressure. Distillation of the residue gave (p-*dimethylaminophenyl*)*methylphenylphosphine* (8 g.), b. p. 175—176°/0·15 mm. The *methiodide* had m. p. (from chloroform–benzene) 234—235° (Found: C, 49·8; H, 5·6; N, 3·9. $C_{16}H_{21}INP$ requires C, 49·9; H, 5·45; N, 3·65%). The *methobromide* had m. p. (from chloroform–benzene) 252—253° (Found: C, 56·65; H, 6·3; N, 3·95. $C_{16}H_{21}BrNP$ requires C, 56·7; H, 6·2; N, 4·15%).

A suspension of the methobromide (3·8 g.) in tetrahydrofuran (150 ml.) was treated with ethereal 1·15N-butyl-lithium (11 ml.) and stirred at room temperature for 1 hr. Benzophenone (2·25 g.) in ether (25 ml.) was added and the resulting white suspension refluxed overnight. Solvent was then removed and the residue shaken with ether and dilute hydrochloric acid. The ether extract was washed with water, dried, and evaporated, and the residue distilled to give 1,1-diphenylethylene (1·9 g.), b. p. 140—141°/14 mm.

(p-*Dimethylaminophenyl*)*dimethylphosphine*. To a stirred solution of methylmagnesium iodide, prepared from magnesium (11·2 g.) and methyl iodide (63 g.) in ether (250 ml.), cooled in ice–salt, *p*-dimethylaminophenyldichlorophosphine (34 g.) in ether (200 ml.) was added during 2 hr. The solution was set aside at room temperature for 1 hr., then cooled, and saturated aqueous ammonium chloride (600 ml.) added. The ethereal layer was dried and evaporated, and the residue distilled to give (*p*-dimethylaminophenyl)dimethylphosphine (19·5 g.), b. p. 86—88°/0·2 mm.

Treatment of the phosphine in benzene with benzyl bromide gave the *phosphonium bromide*, m. p. (from water) 217—219° (Found: C, 58·1; H, 6·3; N, 3·8. $C_{17}H_{22}BrNP$ requires C, 57·9; H, 6·5; N, 4·0%). Similar treatment with phenacyl bromide gave the *phenacylphosphonium bromide*, m. p. (from ethanol) 249—250° (decomp.) (Found: C, 57·3; H, 6·0; N, 3·5. $C_{18}H_{23}BrNOP$ requires C, 56·8; H, 6·0; N, 3·7%). With aqueous alkali at 0°, this gave *benzoylmethylene*-(p-*dimethylaminophenyl*)*dimethylphosphorane*, m. p. (from benzene–light petroleum) 136—137° (Found: N, 4·8. $C_{18}H_{22}NOP$ requires N, 4·7%).

A solution of this phosphorane (3·0 g.) and benzaldehyde (1·06 g.) in benzene (50 ml.) was refluxed for 12 hr., cooled, and washed with dilute hydrochloric acid and with water.

Evaporation, and crystallisation of the residue from aqueous ethanol, gave benzylideneacetophenone (76%), m. p. 58·5—59·5°.

One of us (D. M. W.) acknowledges a maintenance grant from the Department of Scientific and Industrial Research.

THE UNIVERSITY, LEEDS, 2. [*Received, December 5th,* 1960.]

---

406. *Synthesis and Stereochemistry of Heterocyclic Phosphorus Compounds. Part II.* Loss of Optical Activity in the Reduction of (+)-2-Carboxy-9-phenyl-9-phosphafluorene 9-Oxide.*

By I. G. M. CAMPBELL and J. K. WAY.

The preparation of a group of 9-phenyl-9-phosphafluorene 9-oxides by cyclisation of 2-biphenylylphenylphosphinic acids, and the reduction of two of these oxides to 9-phenyl-9-phosphafluorenes are described. 2-Carboxy-9-phenyl-9-phosphafluorene 9-oxide has been resolved by separation of the diastereoisomeric amides obtained from (+)- and from (−)-1-phenylethylamine. Reduction of the (+)-oxide, $[\alpha]_D$ +126°, with lithium aluminium hydride gave 2-hydroxymethyl-9-phenyl-9-phosphafluorene with complete loss of optical activity. This result and the retention of activity observed in the reduction of the azaphosphaphenanthrene oxide (Part I) are discussed.

IN Part I of this series we described the reduction of the (+)- and the (−)-form of 10-*p*-dimethylaminophenyl-9,10-dihydro-9-aza-10-phosphaphenanthrene 10-oxide to the active phosphines with reversal of the sign of rotation. Unfortunately, these phosphines were unsuitable for racemisation experiments as they were sensitive to atmospheric oxygen in solution at room temperature, and consequently no estimate of the optical stability of this type of 3-covalent phosphorus compound could be obtained. An additional disadvantage of the molecule was the complicating factor of the nitrogen–phosphorus ring which, if rigidly puckered, might cause dissymmetry. To avoid these difficulties we decided to study 9-phenyl-9-phosphafluorene system (V) in which the phosphorus atom occurs at the apex of a simple pyramidal molecule. It was hoped that compounds of this type would sufficiently resemble aromatic phosphines to be unaffected by air at low temperatures and consequently, if resolution were successful, measurement of the rates of racemisation would provide an estimate of the optical stability of tercovalent phosphorus compounds.

The 9-phenyl-9-phosphafluorenes were prepared by the routes shown. The 2-biphenylylphenylphosphinic acids (III) were obtained from the corresponding 2-aminobiphenyls (I) either by Doak and Freedman's diazonium fluoroborate method [1] or through the Grignard reagent from the iodide (II) by the method of Burger and Dawson.[2] The latter method where applicable gave considerably better yields.

Cyclisation of the phosphinic acids to the oxides (IV) presented considerable difficulty. As stated in a preliminary note,[3] reagents and conditions which caused ring closure of the corresponding arsinic and stibinic acids were without effect on the phosphinic acids, and the use of aluminium chloride as catalyst in the normal Friedel–Crafts reaction on the chloride of the acid (III; R = R′ = R″ = H) also failed. But the use of a large excess

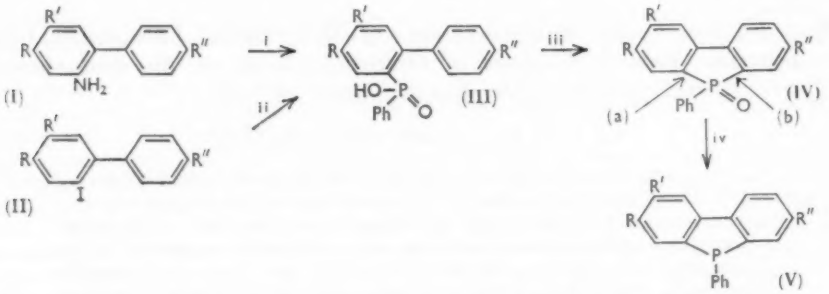
* Part I, *J.*, 1960, 5034.

[1] Doak and Freedman, *J. Amer. Chem. Soc.*, 1952, **74**, 2884.
[2] Burger and Dawson, *J. Org. Chem.*, 1951, **16**, 1250.
[3] Campbell and Way, *Proc. Chem. Soc.*, 1959, 231.

XUM

of phosphorus pentachloride in nitrobenzene at temperatures ranging from 160° to 180° for 4—10 hr. effected the intramolecular cyclisation and the 9-phenyl-9-phosphafluorene 9-oxides (IV) were obtained in 20—80% yields.

Although the mechanism of this reaction was not studied in detail, the characteristic features of an electrophilic substitution were obvious—a methyl group in the biphenylyl system facilitated cyclisation and a nitro-group impeded it. Optimum yields were obtained when three molecular proportions of phosphorus pentachloride were used and we



Reagents: (i) Diazonium fluoroborate + $PhPCl_2$ in EtOAc. (ii) Mg in Et_2O, then $PhPCl_2$, followed by H_2O_2. (iii) PCl_5 in $PhNO_2$, then H_2O. (iv) $LiAlH_4$ in Bu^n_2O and C_6H_6.

suggest that the phosphinyl chloride, Ar_2POCl, first formed is converted in the high-temperature reaction into the trichloride, Ar_2PCl_3, which, in the presence of phosphorus pentachloride, is encouraged to ionise as $[Ar_2PCl_2]^+[PCl_6]^-$. Cyclisation by attack of the positive phosphorus on the adjacent benzene ring of the biphenylyl system would then follow.

This conversion, $Ar_2POCl \longrightarrow Ar_2PCl_3$, has apparently not been described although triarylphosphine dichlorides, Ar_3PCl_2, are obtained by the reaction of phosphorus pentachloride on triarylphosphine oxides.[4] The few known diarylphosphine trichlorides are not well characterised and have been made by addition of chlorine to monochlorides or by chlorination of dithiophosphinic acids.[5] They are described as crystalline solids, very easily hydrolysed, and similar in property to phosphorus pentachloride. As the latter is known to exist as $[PCl_4]^+[PCl_6]^-$, the suggested ionisation of the diarylphosphine trichlorides is not improbable, and self-ionisation $[Ar_2PCl_2]^+[Ar_2PCl_4]^-$ may also be possible.

In the cyclisation of 5-bromo-2-biphenylylphenylphosphinic acid, halogen exchange occurred and the product was 3-chloro-9-phenyl-9-phosphafluorene 9-oxide in place of the 3-bromo-compound. The chloro-oxide was obtained in 65% yield and the acid recovered (10%) was the original bromo-acid. Presumably, therefore, halogen exchange occurs, either in the reacting species when the phosphorus atom becomes positively charged and attack at the *para*-position is facilitated, or after cyclisation is completed.

Examination of the infrared spectra of the phosphinic acids and of the oxides confirms the structure of both. In addition to the bands expected for 1,2-, 1,4-, and 1,2,4-substituted benzenoid compounds (where appropriate), the characteristic P–Ph absorption occurs in both types between 1435 and 1445 cm.$^{-1}$; the strong P=O band occurs for the acids in the range 1180—1225 cm.$^{-1}$ but in a much narrower range, 1200—1210 cm.$^{-1}$, for the oxides [6] other than the 2-carboxy- and 2-hydroxymethyl derivatives where hydrogen-bonding lowers the frequency to 1170 cm.$^{-1}$. Of the three broad absorption bands at 1540—1760, 2260—2460, and 2500—2800 cm.$^{-1}$ present in all the phosphinic acids

[4] Collie and Reynolds, *J.*, 1915, **107**, 367.
[5] Michaelis, *Annalen*, 1901, **315**, 43; Higgins, Vogel, and Craig, *J. Amer. Chem. Soc.*, 1955, **77**, 1864.
[6] Bellamy, " The Infra-red Spectra of Complex Molecules," Methuen, London, 1958.

examined [absorption which has been ascribed [7] to the group X:O(OH) where X = P, As, S, or Se], the two higher frequency bands do not occur in the spectra of the oxides. Further, all five phosphinic acids show a consistent medium-strong band at 950 or 960 cm.$^{-1}$, and no absorption in this region is shown by any of the oxides of this series except the carboxylated member. Bellamy and Beecher [8] have tentatively assigned absorption at 980 cm.$^{-1}$ to a P–O stretching vibration of quinquevalent phosphorus compounds containing the group >PO·O$^-$ and >PS·O$^-$, and our results appear to corroborate this view, particularly as the P–O–C linkage, also said to absorb in this region,[9] is absent for the compounds examined.

2-Carboxy-9-phenyl-9-phosphafluorene 9-oxide, the compound chosen for resolution experiments, was obtained in good yield by oxidation of the 2-methyl oxide (IV; R = Me, R′ = R″ = H) with potassium permanganate in pyridine under conditions similar to those used by Morgan and Herr [10] for the oxidation of *p*-tolyl- to *p*-carboxyphenyl-phosphine oxides. Unfortunately, the acid failed to give crystalline salts with any of the wide variety of alkaloids tested or with (−)-1-phenylethylamine or (+)-amphetamine (see Experimental section). However, the resolution was successfully carried out by fractional crystallisation of the (+)- or (−)-1-phenylethylamides. These were obtained by heating the acid with an excess of the active amine at its boiling point for 6—8 hr. No optical activity was observed in the small amounts of acid regained from amide formation. The product from the reaction with the (−)-amine was a mixture of amides, $[\alpha]_D$ +51·2°, which was separated by crystallisation from ethanol into the less soluble (−)-acid–(−)-amide, $[\alpha]_D$ −37·9°, and (after dilution with water and further crystallisation) the (+)-acid–(−)-amide, $[\alpha]_D$ +211·5°. Similarly, the (+)-amine gave a mixture of amides, $[\alpha]_D$ −51·9°, separated into (+)acid–(+)-amide, $[\alpha]_D$ +38·6°, and (−)-acid–(+)-amide, $[\alpha]_D$ −212·0°. The isolation of the less soluble amide in optically pure state was relatively easy; but careful control of the conditions of crystallisation was necessary if the more soluble amide was not to be contaminated by the less soluble isomer, in which case it required repeated recrystallisation before reaching optical purity.

Considerable difficulty was met in the isolation of the optically active acids from the amides. In the first attempts, the amide, $[\alpha]_D$ +211·5°, was heated with aqueous-methanolic potassium hydroxide for an hour and gave, on acidification, a product with $[\alpha]_D$ +31·4°, but the diastereoisomeric amide, $[\alpha]_D$ −37·9°, on similar treatment also gave dextrorotatory material, $[\alpha]_D$ +32·6°. The products appeared to be hydrated acids which could not be satisfactorily recrystallised. On analysis they showed the correct carbon content for the phosphafluorene oxide carboxylic acid but very high hydrogen values. Repetition of this hydrolysis with the amides of $[\alpha]_D$ +38·6° and $[\alpha]_D$ −212·0° gave similar acids with $[\alpha]_D$ −32·4° and −31·2°, respectively. When all four products were found to contain nitrogen it became obvious that the resolving group had not been removed, but, instead, ring fission had occurred at either (a) or (b) in (IV) and the products were phosphinic and not carboxylic acids. Consequently, the asymmetry of the cyclic phosphine oxide had been destroyed and the rotations observed were derived from the (+)- and the (−)-1-phenylethylamido-group. This result was entirely unexpected as the carbon–phosphorus bond is comparable in strength with the carbon–carbon bond [11] and is broken only under drastic conditions such as the fusion of phosphine oxides with alkali (phosphinic acids are then obtained [12]).

In order to discover if ring fission had occurred at (a) or (b) in compound (IV; R = R′ = H, R″ = CO·NH·CHMePh) the product from the alkaline hydrolysis, having $[\alpha]_D$

[7] Braunholtz, Hall, Mann, and Sheppard, *J.*, 1959, 868.
[8] Bellamy and Beecher, *J.*, 1953, 728.
[9] Thomas, *J. Appl. Chem.*, 1957, 198.
[10] Morgan and Herr, *J. Amer. Chem. Soc.*, 1952, **74**, 4526.
[11] Huggins, *J. Amer. Chem. Soc.*, 1953, **75**, 4123.
[12] Horner, Hoffmann, and Wippel, *Chem. Ber.*, 1958, **91**, 64.

XUM

$-32{\cdot}4°$, was further hydrolysed by prolonged heating with ethanolic hydrochloric acid. Loss of the phenylethylamido-group gave an optically inactive acid which is almost certainly 4′-carboxy-2-biphenylylphenylphosphinic acid. Its infrared spectrum closely resembles that of the acid (III; R = R′ = H, R″ = NO_2), a compound of known structure with substituents in the positions expected if the phosphafluorene ring opened at (b). Peaks at 1090, 1100, and 1140 cm.$^{-1}$, indicative of 1,2- and 1,4-disubstituted benzenes, are present in the spectra of both acids. On the other hand, the acid (III; R = Me, R′ = R″ = H) substituted similarly to a product resulting from fission at (a) shows the extra band associated with 1,2,4-substitution,[5] *i.e.*, bands at 1070, 1100, 1150, and 1165 cm.$^{-1}$. Preferential cleavage of the bond from phosphorus to the ring holding the amido-group is in line with Horner's experience [12] that the most electronegative group separates from phosphorus in the fusion of phosphine oxides with sodium hydroxide.

The isolation of the optically pure (+)- and (−)-phosphafluorene oxide carboxylic acids was finally achieved by prolonged hydrolysis with hydrochloric acid in ethanol, a method used by Marckwald [13] in his resolution of (±)-1-phenylethylamine through amide formation with quinic acid. He noted that racemic 1-phenylethyl chloride was produced in the course of hydrolysis and we have confirmed this observation, but the by-product was only a minor disadvantage in our case. By this method the amide of $[\alpha]_D$ $+38{\cdot}6°$ gave acid, m. p. 250—251°, $[\alpha]_D^{20}$ $+126{\cdot}0° \pm 2°$ (in 0·1N-sodium hydroxide), in 80% yield; and from the amide of $[\alpha]_D$ $-212°$, the enantiomeric acid, m. p. 250—251°, $[\alpha]_D^{20}$ $-126{\cdot}1° \pm 1{\cdot}7°$, was obtained in 66% yield. A large difference in solubility in ethanol between the (±)-acid and the (+)- or (−)-form made it possible to isolate optically pure acid from partly resolved specimens.

Reduction of the phosphafluorene oxides to phosphafluorenes was carried out by the method of Horner *et al.*[14] with lithium aluminium hydride in dibutyl ether and benzene at 80°. 9-Phenyl-9-phosphafluorene,[15] m. p. 90—92°, was obtained from the corresponding oxide in rather poor yield, but, contrary to the experience of others,[16] we found no evidence for the fission of a C–P bond. Preferential removal of oxygen without reduction of the carboxyl group in 2-carboxy-9-phenyl-9-phosphafluorene 9-oxide (IV; R = R′ = H, R″ = CO_2H) was not achieved—sodium borohydride had no effect on the P=O bond—and the product of reduction by lithium aluminium hydride was a mixture of 2-hydroxymethyl-9-phenyl-9-phosphafluorene and its 9-oxide. The phosphine was obtained crystalline (m. p. 52—54°) only when it retained a molecule of ethanol, and removal of this gave an amorphous residue, m. p. 38—42°, which was readily oxidised in air, particularly when in solution. The presence of traces of oxide in the product was indicated by low analytical values for carbon and by a small peak in the P=O region of the infrared spectrum.

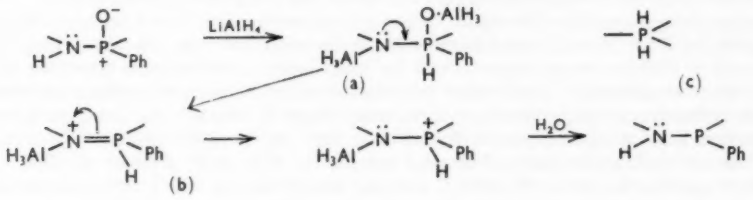
Reduction of the *dextro*-form of the acid, $[\alpha]_D$ $+126°$, gave the same two products and resulted in complete loss of optical activity. The oxide must therefore result from re-oxidation of the phosphine in the course of isolation, as the original acid is optically stable in alkaline solution at 100° and is not likely to be racemised under the conditions of reduction

Racemisation of the phosphafluorene is not unexpected in the light of Weston's estimate [17] that a simple pyramidal phosphine should have a half-life at 67° of only 2 hr., but is in direct contrast with our results in the reduction of the azaphosphaphenanthrene oxide (Part I). The optical activity of the phosphine isolated in the latter case could, of course, be ascribed to the asymmetry of a skew molecule, a possibility which we discussed but dismissed for several reasons. However, if the azaphosphaphenanthrene is capable

[13] Marckwald, *Ber.*, 1905, **38**, 801.
[14] Horner, Hoffmann, and Beck, *Chem. Ber.*, 1958, **91**, 1583.
[15] Wittig and Geissler, *Annalen*, 1953, **580**, 44.
[16] Issleib, Hein, and Rabold, *Z. anorg. Chem.*, 1956, **287**, 208.
[17] Weston, *J. Amer. Chem. Soc.*, 1954, **76**, 2645.

XUM

of retaining a pyramidal configuration during reduction at 80°, why is the phosphafluorene completely racemised under essentially the same conditions? We suggest that participation by nitrogen, as in the hydrogenolysis of amides,[18] results in a stereospecific reduction of the azaphosphaphenanthrene as shown in the partial formulæ annexed.



Attack by hydride ion would lead to the intermediate (a) in which phosphorus has the trigonal bipyramidal form, and loss of oxygen would occur with inversion, though hydride transfer from the $OAlH_3$ group by an S_Ni reaction of the four-centre type is also possible and would result in retention. The intermediate (b) resembles a Wittig reagent which is known to retain configuration in reactions with carbonyl compounds [19] and might therefore be expected to give active phosphine on decomposition with water.

In the absence of nitrogen, an intermediate of type (b) is impossible and addition of hydride ion to the phosphafluorene oxide may occur by both S_N2 and S_Ni mechanisms to give a symmetrical intermediate (c) with consequent loss of activity. If, however, only one mechanism of hydrogen transfer is involved the initially active phosphine must undergo thermal racemisation. However, the azaphosphaphenanthrene can be isolated in optically active form from reduction under the same conditions, so the energy of activation of its racemisation must be considerably higher than that of the phosphafluorene. No doubt the energy barrier created by the repulsion of the lone pairs on the nitrogen and on the phosphorus would at least discourage the attainment of the planar transition state.

Experimental

Rotations were measured for absolute EtOH solutions in 2 dm. tubes (*c* 0·2—0·4) at room temperature unless otherwise stated. Infrared measurements were taken for Nujol mulls on the Unicam S.P. 100 spectrophotometer.

Preparation of 2-Biphenylylphenylphosphinic Acids.—(a) *Diazonium fluoroborate method.* Conditions similar to those recommended by Doak and Freedman [1] were used to prepare the phosphinic acids. For example, 2-aminobiphenyl (0·1 mole) was converted into the diazonium fluoroborate, and the dry salt was decomposed in ethyl acetate (200 ml.) in the presence of phenylphosphonous dichloride (0·1 mole) and copper bronze (2 g.). After steam-distillation to remove solvent and by-products (biphenyl and 2-chlorobiphenyl) the sticky brown residue was separated from the aqueous layer and warmed with 10% aqueous sodium hydroxide (25—30 ml.). From the filtered solution the sodium salt of the phosphinic acid crystallised as matted brown needles which were separated and washed with a little acetone. Acidification of a solution of this salt gave 2-biphenylylphenylphosphinic acid (III; R = R′ = R″ = H),[3] m. p. 180—181° (9—10%), after crystallisation from acetic acid or ethanol–water.

Similar procedure with 2-amino-4′-nitrobiphenyl gave 4′-nitro-2-biphenylylphenylphosphinic acid (III; R = R′ = H, R″ = NO_2), m. p. 234—237°, as buff needles from ethanol–water in 20—23% yield. 2-Amino-5-bromobiphenyl gave the *5-bromo-compound* (III; R = R″ = H, R′ = Br), m. p. 193—194°, which separated as colourless needles from aqueous ethanol in 11%

[18] Gaylord, " Reduction with Complex Metal Hydrides," Interscience Publ. Inc., New York, 1959, p. 545.
[19] Bladé-Font, VanderWerf, and McEwen, *J. Amer. Chem. Soc.*, 1960, **82**, 2396.

XUM

yield (Found: C, 58·1; H, 3·9. $C_{19}H_{14}BrO_2P$ requires C, 58·0; H, 3·8%). *4-Methyl-2-biphenylylphenylphosphinic acid* (III; R = Me, R′ = R″ = H), m. p. 144—145°, was obtained in only 4—5% yield by this method; it crystallised from ethyl acetate–light petroleum (b. p. 60—80°) in elongated prisms (Found: C, 73·8; H, 5·9. $C_{19}H_{17}O_2P$ requires C, 74·0; H, 5·6%).

(b) *Grignard method* (cf. ref. 2). Phenylphosphonous dichloride (4·7 g.) in ether (50 ml.) was added slowly to 2-biphenylylmagnesium iodide obtained from 2-iodobiphenyl (7 g.) and magnesium (0·6 g.) in ether (100 ml.). When the vigorous reaction had subsided the mixture was boiled for 1 hr., cooled, and treated with 2N-hydrochloric acid (25 ml.). This produced a heavy oil in addition to the aqueous and the ether layer. The aqueous layer was discarded and the ether evaporated. The residue was treated with 10% aqueous sodium hydroxide and hydrogen peroxide (5 ml.; 30-vol.); a vigorous reaction resulted in complete dissolution. Acidification gave 2-biphenylylphenylphosphinic acid, m. p. 180—181° (1·5 g., 20%) after crystallisation from acetic acid. The *ethyl ester*, m. p. 112—114° (Found: C, 73·9; H, 5·9. $C_{20}H_{19}O_2P$ requires C, 74·5; H, 5·9%), and the *anilide*, m. p. 202—204° (Found: C, 77·5; H, 5·4. $C_{24}H_{20}NOP$ requires C, 78·0; H, 5·5%), were obtained by treatment of the acid with thionyl chloride followed by ethanol or aniline, respectively.

2-Iodo-4-methylbiphenyl, b. p. 110—112°/0·3 mm., was obtained from the corresponding amine by the method of Zaheer and Faseeh [20] in 46% yield. Phenylphosphonous dichloride (7 ml.) in ether (75 ml.) was added to the filtered Grignard reagent prepared from 2-iodo-4-methylbiphenyl (17 g.) and magnesium (1·4 g.) in ether (100 ml.). During the addition (15 min.) the mixture was stirred rapidly and when the vigorous reaction had subsided heating was continued for 45 min. After cooling, the mixture was shaken with 2N-sulphuric acid (50 ml.), and hydrogen peroxide (5 ml.; 100-vol.) was added dropwise. After 30 minutes' stirring, the organic layer was separated and evaporated. The dark residue was extracted with hot 10% aqueous sodium hydroxide containing a little hydrogen peroxide. The sodium salt separated from the filtered solution on cooling, and was filtered off and washed with ether. Acidification of a solution of this salt gave the crude acid (7·7 g.) which, after crystallisation from ethyl acetate–light petroleum (b. p. 60—80°), had m. p. 144—145° (5·9 g., 33%).

Cyclisation of 2-Biphenylylphenylphosphinic Acids.—(*a*) 2-Biphenylylphenylphosphinic acid was regained from polyphosphoric acid after being heated at 120° for 30 min., but at 160° some decomposition occurred and biphenyl (10%) was isolated in addition to unchanged acid.

(*b*) Concentrated sulphuric acid at 110° (20 min.) apparently caused sulphonation of the phosphinic acid, for complete dissolution occurred on addition of the reaction mixture to water. Attempts to isolate sulphonated acids by formation of the magnesium or barium salts failed.

(*c*) The phosphinic acid (1 g.) was converted into the acid chloride by warming it with an excess of thionyl chloride in chloroform, and the viscous oil obtained was heated in carbon disulphide (20 ml.) with aluminium chloride (0·5 g.) for 3 hr. The mixture was shaken with N-hydrochloric acid, water, and saturated sodium hydrogen carbonate solution. Evaporation of the carbon disulphide gave a small sticky residue and acidification of the alkaline extract gave unchanged acid of m. p. 175—180° (0·8 g.). This experiment was repeated with nitrobenzene (10 ml.) as solvent and heating at 160° for 4 hr. The cooled mixture was poured into water and steam-distilled to remove nitrobenzene. The black residue was soluble in aqueous sodium hydrogen carbonate. Acidification gave unchanged acid, m. p. 170—180° (0·6 g.).

(*d*) A mixture of the acid (III; R = R′ = R″ = H) (1 g.) and phosphorus pentachloride (1·5 g.) was heated for 4 hr. under reflux, with exclusion of moisture, at 170—180°. The cold mixture was poured into water and steam-distilled to remove nitrobenzene. The sticky residue was separated from the aqueous layer and extracted with 10% aqueous sodium hydroxide, leaving a brown solid (0·4 g.) which was crystallised from aqueous ethanol and gave 9-phenyl-9-phosphafluorene 9-oxide, m. p. 167—168° (0·25 g.) (Found: C, 78·0; H, 4·75. Calc. for $C_{18}H_{13}OP$: C, 78·25; H, 4·7%). Acidification of the alkaline extract gave unchanged acid (0·5 g.).

The oxide formed a *cadmium iodide complex* in aqueous ethanol which separated from ethyl acetate containing a trace of ethanol in diamond-shaped plates, m. p. 200—202° [Found: C, 46·9; H, 2·8. $(C_{18}H_{13}OP)_2CdI_2$ requires C, 47·1; H, 2·85%]. The *mercuric chloride complex* made similarly had m. p. 145—147°, and contained the constituents in different proportions [Found: C, 48·5; H, 2·75. $(C_{18}H_{13}OP)_2(HgCl_2)_2$ requires C, 48·6; H, 2·8%].

[20] Zaheer and Faseeh, *J. Indian Chem. Soc.*, 1944, **21**, 27.

Treatment of the acid (III; R = R′ = H, R″ = NO_2) (0·8 g.) by process (*d*) gave 2-*nitro*-9-*phenyl*-9-*phosphafluorene* 9-*oxide* (IV; R = R′ = H, R″ = NO_2) (0·15 g.), m. p. 203° (Found: C, 67·0; H, 4·1. $C_{18}H_{12}NO_3P$ requires C, 67·3; H, 3·8%), and unchanged acid (0·48 g.).

By process (*d*) but with the quantity of phosphorus pentachloride increased to 2 g. and the period of heating to 8 hr. at 160—170°, the acid (III; R = R″ = H, R′ = Br) (1 g.) gave a cyclic oxide, m. p. 227—228° (0·65 g.), and 0·1 g. of acid was regained. The oxide was found to contain chlorine but no bromine, and was presumably 3-*chloro*-9-*phenyl*-9-*phosphafluorene* 9-*oxide* (IV; R = R″ = H, R′ = Cl) (Found: C, 69·4; H, 4·3; Cl, 11·7; P, 10·3. $C_{18}H_{12}ClOP$ requires C, 69·6; H, 3·9; Cl, 11·4; P, 10·0%).

2-*Methyl*-9-*phenyl*-9-*phosphafluorene* 9-*Oxide*.—The acid (III; R = Me, R′ = R″ = H) (2 g.) was suspended in "AnalaR" nitrobenzene (12 ml.) and cyclised by heating it with phosphorus pentachloride (4 g.) at 160—165° for 6 hr. The product was isolated as described under (*d*) and was obtained as a glass (1·5 g.) which crystallised with difficulty from ethyl acetate–light petroleum (b. p. 60—80°), giving the pure *oxide* (IV; R = Me, R′ = R″ = H), m. p. 146—147° (Found: C, 78·5; H, 5·0. $C_{19}H_{15}OP$ requires C, 78·6; H, 5·2%). A depression of 27° was observed in a mixed m. p. determination with the uncyclised acid, m. p. 144—145°. Unchanged acid (75 mg.) was regained.

2-*Carboxy*-9-*phenyl*-9-*phosphafluorene* 9-*Oxide*.—The crude 2-methyl-9-phenylphosphafluorene oxide (10 g.) was heated in pyridine (45 ml.) and water (25 ml.) on a water-bath. Potassium permanganate (19·5 g.) was added to the hot solution in small portions during 2—3 hr. A further 30 ml. of water were added to keep the mixture fluid. Heating was continued for 5 hr., then pyridine was removed by steam-distillation, and manganese dioxide by filtration, and the alkaline solution was acidified. The precipitated acid crystallised from aqueous ethanol, and 2-*carboxy*-9-*phenyl*-9-*phosphafluorene* 9-*oxide* (II; R = CO_2H, R′ = R″ = H), m. p. 309—313° (darkening) (5·9 g.), separated as colourless needles. Recrystallisation raised the m. p. to 323—326° (Found: C, 70·9; H, 4·1. $C_{19}H_{13}O_3P$ requires C, 71·25; H, 4·1%). 2-Methyl-9-phenylphosphafluorene oxide (0·9 g.) was recovered from the precipitated manganese dioxide after reduction.

Optical Resolution of 2-*Carboxy*-9-*phosphafluorene* 9-*Oxide*.—All attempts to resolve the acid by salt formation with optically active bases failed. Salts made by dissolving the acid with the equivalent weight of quinine, quinidine, ephedrine, brucine, or strychnine, in various solvents, separated as gums. Solutions of the acid with one or two equivalents of (−)-1-phenylethylamine or (+)-amphetamine in ethanol deposited oils on addition of ether, and crystals which separated (after several weeks) from the attempt with (−)-1-phenylethylamine proved to be acid, m. p. 310°

(a) *Resolution through the* (−)-1-*phenylethylamide*. The acid (1 g.) and (−)-1-phenylethylamine (3 ml.) were heated together at the b. p. for 3 hr., cooled, and poured into 4N-hydrochloric acid (20 ml.). The solid which separated was extracted with saturated sodium hydrogen carbonate solution, leaving the amide (0·75 g.) undissolved. The acid (0·35 g.) was regained from the alkaline extract. The amide, $[\alpha]_D$ +51·2°, crystallised from ethanol and gave a first fraction (0·25 g.) with $[\alpha]_D$ −28·9°. Two further crystallisations of this gave the (−)-*acid-amide* (0·14 g.), as rosettes of needles, m. p. 263—265°, $[\alpha]_D$ −37·9° (Found: C, 76·0; H, 5·3. $C_{27}H_{22}NO_2P$ requires C, 76·6; H, 5·2%).

Dilution of the filtrate from the first separation with water gave a second fraction of amide (0·23 g.), $[\alpha]_D$ +189·3°, which when recrystallised from ethanol gave optically pure (+)-*acid amide* (0·14 g.), m. p. 273—275°, $[\alpha]_D$ +211·5°, as highly refracting prisms (Found: C, 75·9; H, 5·3%). Amide which separated as a third fraction from the original crystallisation was contaminated by a yellow gum.

(b) *Resolution through the* (+)-1-*phenylethylamide*. The acid (2 g.) was suspended in (+)-1-phenylethylamine (5 ml.; $[\alpha]_D$ +34·7° in chloroform) and heated at the b. p. for 5 hr. The cooled liquid was poured into 2N-hydrochloric acid (50 ml.), and the solid obtained was filtered and extracted with saturated aqueous sodium hydrogen carbonate. Acid (0·22 g.) was regained from the extract. The amide (2·25 g.) had $[\alpha]_D$ −51·9° and when crystallised from ethanol (15 ml.) gave a first fraction (0·65 g.) with $[\alpha]_D$ +34·5° which was raised to $[\alpha]_D$ +38·6° by one further crystallisation. This optically pure (+)-*acid*–(+)-1-*phenylethylamide* (0·45 g.) had m. p. 265—266° and separated as stout needles (Found: C, 76·7; H, 5·0; N, 3·3. $C_{27}H_{22}NO_2P$ requires C, 76·6; H, 5·2; N, 3·3%). A second fraction of amide (0·72 g.) was obtained from the mother-liquor by dilution with water (15 ml.) and had $[\alpha]_D$ −171·9°. One crystallisation

of this from ethanol gave the pure (−)-*acid*–(+)-1-*phenylethylamide*, m. p. 274—275°, $[\alpha]_D$ −212·0° (0·50 g.), as heavy prisms (Found: C, 76·55; H, 5·1; N, 3·45%). A third fraction of amide, $[\alpha]_D$ −43·4° (0·27 g.), and a fourth, $[\alpha]_D$ −7·8° (0·25 g.), were separated but optically pure material was not obtained from them.

A repetition of this resolution with 2·4 g. of acid gave (+)-acid-amide, $[\alpha]_D$ +37·5° (0·61 g.), and (−)-acid amide, $[\alpha]_D$ −211·0° (0·31 g.).

Hydrolysis of the Active Amides.—The (+)-acid–(−)-amide, $[\alpha]_D$ +211·5° (0·14 g.), was boiled with a 25% solution (5 ml.) of potassium hydroxide in methanol–water (3 : 1) for 1 hr. The solution was chilled, diluted, and acidified with N-sulphuric acid at 0°. The precipitated *acid* (0·14 g.), m. p. 140—145° (decomp.) softening at 105°, $[\alpha]_D$ +32·4°, appeared to be hydrated (Found: C, 71·25; H, 5·2. $C_{19}H_{13}O_3P$ requires C, 71·25; H, 4·1%).

The (−)-acid–(−)-amide, $[\alpha]_D$ −37·9° (0·1 g.), gave, on similar treatment, an *acid* (85 mg.) which had $[\alpha]_D$ +32·6° and m. p. 140—150°, softening at 108° (Found: C, 71·2; H, 5·2%).

Hydrolysis of the (+)-acid–(+)-amide, $[\alpha]_D$ +38·5° (0·2 g.), by the same method gave an *acid* (0·17 g.), $[\alpha]_D$ −32·4°, while the (−)-acid–(+)-amide, $[\alpha]_D$ −212·0° (0·2 g.), gave an *acid* (0·17 g.), $[\alpha]_D$ −31·2° (Found: C, 71·0; H, 5·2; and C, 71·1; H, 5·2%, respectively). Both products had the same indefinite m. p. 140—150° with previous softening, and could not be recrystallised satisfactorily. Both gave a positive test for nitrogen. The acid of $[\alpha]_D$ −32·4° (0·1 g.) was dissolved in ethanol (1 ml.) and hydrolysed by boiling concentrated hydrochloric acid (2 ml.) for 5 hr. Dilution of the cooled mixture gave a solid (0·05 g.) which, after crystallisation from ethanol–water or from dilute acetic acid, had m. p. 292° (softening from 285°) and was optically inactive (Found: C, 67·25; H, 4·2. $C_{19}H_{15}O_4P$ requires C, 67·45; H, 4·5%).

Isolation of (+)- *and* (−)-2-*Carboxy*-9-*phenyl*-9-*phosphafluorene* 9-*Oxide*.—The amide, $[\alpha]_D$ +37·5° (0·65 g.), was suspended in ethanol (5 ml.) and concentrated hydrochloric acid (10 ml.) and boiled under reflux for 12 hr. The cooled mixture was poured into water, and the precipitate was collected, dissolved in 2N-sodium hydroxide, and filtered from a small sticky residue. Acidification of the filtrate gave the (+)-*acid*, m. p. 250—251°, $[\alpha]_D^{20}$ +126·0° ± 2° (*c* 0·238 in 0·1N-sodium hydroxide) (0·41 g., 83%) (Found: C, 71·1; H, 4·1%).

Similar treatment of the (−)-amide, $[\alpha]_D$ −212·0° (0·2 g.), gave the (−)-*acid*, m. p. 250—251°, $[\alpha]_D^{20}$ −126·1° ± 1·7° (*c* 0·283 in 0·1N-sodium hydroxide) (0·11 g.) (Found: C, 70·8; H, 4·1%).

A specimen of (+)-acid, $[\alpha]_D^{20}$ +81·1° (0·1 g.), obtained in this way from optically impure amide, was extracted with hot ethanol (3 ml.) and filtered. The filtrate on cooling deposited pure (+)-acid, m. p. 250—251°, $[\alpha]_D$ +125·9° ± 2·4° (45 mg.). The residue had m. p. 300° and showed a negligible rotation. The acids had $[\alpha]_D^{20}$ +107·1° and −106·3° in absolute ethanol (*c* 0·140 and 0·127 respectively) and were unchanged in rotation after 3 weeks at room temperature. A solution of the acid in 0·1N-sodium hydroxide, α_D^{19} +0·61°, was boiled under reflux for 1 hr. and cooled rapidly to 19°. The rotation of the solution was unchanged then, and also after a further 2 hours' heating.

Reduction of 9-*Phenyl*-9-*phosphafluorene* 9-*Oxides*.—(a) *Sodium borohydride*. A mixture of the oxide (IV; R = R′ = R″ = H) (0·2 g.) and sodium borohydride (0·2 g.) in methanol (5 ml.) was warmed on a water-bath for 3 hr. Addition of water to the cold solution precipitated unchanged oxide (0·15 g.), m. p. 162—165° (after crystallisation from aqueous ethanol).

The oxide (IV; R = R′ = H, R″ = CO_2H) (0·5 g.) was neutralised with 0·1N-sodium hydroxide, sodium borohydride (0·5 g.) in water (2 ml.) was added, and the mixture was kept at room temperature for 3 days. Acidification then gave unchanged oxide (0·45 g.). The oxide was also regained when the mixture was kept at 50° for 24 hr. and at 100° for 10 hr.

(b) *Lithium aluminium hydride*. The oxide (IV; R = R′ = R″ = H) (0·47 g.), dissolved in benzene (5 ml.), was added dropwise to lithium aluminium hydride (0·2 g.) suspended in dibutyl ether (5 ml.) at 80—90°. The mixture was heated on a water-bath for 5 hr., cooled, and poured into 20% aqueous sodium hydroxide. The organic layer was separated, washed, dried (Na_2SO_4), and evaporated. The solid residue, on crystallisation from methanol gave 9-phenyl-9-phosphafluorene,[15] m. p. 90—92° (90 mg.). Its infrared spectrum was almost identical with that shown in ref. 15 (m. p. 92—94°). The main ultraviolet absorption band of 9-phenyl-9-phosphafluorene, $\lambda_{max.}$ 270 mμ (ε 14,580), $\lambda_{min.}$ 253 (ε 13,250), shows a bathochromic shift of only 10 mμ compared with that of triphenylphosphine, $\lambda_{max.}$ 260 mμ (ε 12,660). This shift is small compared with that observed for similar arsenic and antimony compounds.[21]

[21] Campbell and Poller, *Chem. and Ind.*, 1953, 1126.

XUM

The oxide (IV; R = R′ = H, R″ = CO_2H) (0·5 g.) was suspended in benzene (10 ml.) and added in small portions to lithium aluminium hydride (0·4 g.) in dibutyl ether (10 ml.) at 80—90° during 0·5 hr. Benzene (5 ml.) was added and the whole heated on a water-bath for 4 hr. and set aside overnight. The mixture was cooled, excess of reagent was decomposed by addition of water, and the whole shaken with N-sulphuric acid (50 ml.). The organic layer was washed, dried, and evaporated *in vacuo*, giving a gum (0·32 g.). A portion (0·25 g.), crystallised from ethanol–light petroleum (b. p. 60—80°), gave solvated *2-hydroxymethyl-9-phenyl-9-phosphafluorene* (V; R = R′ = H, R″ = CH_2·OH), m. p. 52—54° (91 mg.) (Found: C, 75·5, 75·8; H, 6·1, 5·9. $C_{19}H_{15}OP,C_2H_6O$ requires C, 75·0; H, 6·3%). The phosphine was heated *in vacuo* at 100° for 3 hr.; the *anhydrous form* had m. p. 38—42° (Found: C, 77·4; H, 5·0. $C_{19}H_{15}OP$ requires C, 78·6; H, 5·2). Addition of ether to the filtrate from the crystallisation of the phosphine precipitated *2-hydroxymethyl-9-phenyl-9-phosphafluorene 9-oxide* (IV; R = R′ = H, R″ = CH_2OH), m. p. 195—196° (50 mg.) (from ethanol–ethyl acetate) (Found: C, 74·1; H, 4·75. $C_{19}H_{15}O_2P$ requires C, 74·5; H, 4·9%). Methylation of the original gum (70 mg.) gave *2-hydroxymethyl-9-phenyl-9-phosphafluorene methiodide*, m. p. 228—230° (30 mg.) (Found: C, 55·9; H, 3·9. $C_{20}H_{18}IOP$ requires C, 55·6; H, 4·2%).

When the reduction was repeated with the (+)-acid (0·4 g.) and lithium aluminium hydride (0·3 g.), the product (0·32 g.) was optically inactive. It (0·27 g.) was separated by crystallisation from ethanol–light petroleum (b. p. 60—80°) into the phosphafluorene alcohol (150 mg.), m. p. 51—53° (Found: C, 75·2; H, 6·2, and C, 77·8; H, 5·1% after heating *in vacuo*), and the corresponding oxide, m. p. 195—196° (60 mg.) (Found: C, 74·1; H, 4·8%). Methylation of the crude product gave the methiodide, m. p. and mixed m. p. 226—230°. The phosphine, m. p. 52—54°, when boiled in benzene for an hour gave the oxide, m. p. 195—196°, on evaporation of the solvent.

Relevant infrared bands are in the annexed Table.

Main infrared absorption bands of compounds (IV *and* V; R = R′ = H, R″ = CH_2·OH).

Compound IV:	3260b, 3040, 1600, 1482, 1460,† 1440s, 1410w, 1350, 1205, 1175s, 1140, 1120, 1065s, 830, 770, 750s, 735s, 700
Compound V:	3330b, 3040, 1600, 1480, 1455,† 1440s, 1410, 1330, 1208, 1185s, 1140, 1120, 1060s, 895w, 830, 780s, 740s, 700s
Benzyl alcohol: *	3350b, 3030, 2920, 2880, 1500, 1460, 1212, 1090w, 1050s, 1025, 925w, 745, 700

b = broad band, mid-point; s = strong; w = weak; remainder medium. Nujol peaks, 2950b, 2890b, 1465, 1385.

* Liquid film. † The intensity of the 1465 Nujol band is increased relative to the 1385 band owing to the presence of the benzyl CH_2 group.

The authors thank The Chemical Society and Imperial Chemical Industries Limited for financial support, Albright & Wilson, Ltd., for generous gifts of phosphorus intermediates, the D.S.I.R. for a maintenance grant (to J. K. W.), and Dr. J. Hudec for valuable advice and help with the infrared measurements.

THE UNIVERSITY, SOUTHAMPTON. [*Received, December 6th*, 1960.]

XUM

407. *Mechanism of Replacement of Chlorine in* cis- *and* trans-*Chloronitrobis(ethylenediamine)cobalt*(III) *Ions by Thiocyanate in Methanol.*

By S. Ašperger, D. Pavlović, and M. Orhanović.

The rate of replacement of chlorine by thiocyanate in the *cis*-chloronitrobis(ethylenediamine)cobalt(III) ion in methanol solution is independent of the thiocyanate concentration, but that in the *trans*-isomer shows a slight dependence on the thiocyanate concentration and is 14 times (or 28 times if calculated for one chlorine atom only) greater than the rate of the similar replacement in the *trans*-dichlorobis(ethylenediamine)cobalt(III) ion in methanol. The accelerating influence of the nitro-group suggests that this substitution is an S_N2 process involving methanol as the nucleophilic reagent. The negative electromeric effect of the nitro-group causes polarisation of the cobalt atom. The polarisation demand of the binding of the methanol seems to be more important than the loosening of the displaced chlorine which the nitro-group makes more difficult. An analogy is drawn with the aquation of the same complexes.

The kinetics of octahedral substitutions have been studied by several authors, most of the work being done in aqueous solutions because of the insolubility of complex ions in most other solvents. It has been shown that water is not a very suitable solvent, except for very strongly nucleophilic reagents, *e.g.*, hydroxide ion, because it has a higher complex-forming power towards the ions of transition metals than any other solvent except liquid ammonia, so that an intermediate hydrolysis step takes place.[1,2]

Methanol has been considered as a suitable solvent in which a number of direct reactions seem to occur. Brown and Ingold[3] studied the rates of reactions of *cis*-dichlorobis(ethylenediamine)cobalt(III) ion in methanol with seven anions which displace chlorine. They found that four of them (NO_3^-, Br^-, SCN^-, and $^*Cl^-$), all weakly nucleophilic, showed first-order kinetics; for three more strongly nucleophilic anions (NO_2^-, N_3^-, and OMe^-) substitution showed second-order kinetics, with the rates differing widely in order of nucleophilic power. However, Brown and Ingold's kinetic results on the basis of which the S_N1 mechanism was predicted are also in agreement with an S_N2 mechanism involving the solvent methanol as the nucleophilic reagent.

The reactions of *cis*- and *trans*-chloronitrobis(ethylenediamine)cobalt(III) ions with thiocyanate in methanol which we investigated also showed first-order kinetics (complete independence of the rate on the thiocyanate calculated for the *cis*-complex and slight dependence for the *trans*-complex). The comparison of the rates of replacement of chlorine by thiocyanate in methanol in *trans*-chloronitrobis(ethylenediamine)cobalt(III) ion and in *trans*-dichlorobis(ethylenediamine)cobalt(III) ion showed that the replacement in the former complex is about 14 times (or 28 times if calculated for one chlorine atom) faster than in the dichloro-complex. This is not in accordance with a dissociation mechanism, since the polarisation of the cobalt atom by the nitro-group should oppose the heterolysis of the departing halogen, not facilitate it.[2]

Comparison of the rates of replacement of chlorine by thiocyanate in *cis*- and *trans*-chloronitro- and *cis*- and *trans*-dichloro-bis(ethylenediamine)cobalt(III) ions with the corresponding rates of aquation also lends support to the idea that the replacement of chlorine by thiocyanate requires two stages, the first being a rate-determining methanolysis.

[1] Brown, Ingold, and Nyholm, *J.*, 1953, 2674.
[2] Ašperger and Ingold, *J.*, 1956, 2862.
[3] Brown and Ingold, *J.*, 1953, 2680.

Results

Kinetics and Products of the Reaction of trans-*Chloronitrobis(ethylenediamine)cobalt*(III) *Ion with Thiocyanate Ion in Methanol.*—The spectral method was used for measuring the rates of substitutions. For this it was necessary to prepare the complexes in crystalline form and to determine their absorption spectra in methanolic solution. *trans*-Chloronitrobis(ethylenediamine)cobalt(III) nitrate, *cis*-chloronitrobis(ethylenediamine)cobalt(III) chloride, and *trans*- and *cis*-thiocyanatonitrobis(ethylenediamine)cobalt(III) thiocyanate were prepared. Solutions of these complexes were made in absolute methanol dried by Lund and Bjerrum's method.[4] Analyses showed that methanol contained about 0·05% of water. Pearson *et al.* previously found [5] that up to 0·5% of water had no effect on the measured rates for some *trans*-$[CoA_2Cl_2]^+$ complexes in methanol (A = ethylenediamine, propylenediamine, 1,2-dimethylethylenediamine, diaziridine, and tetramethylethylenediamine, respectively).

FIG. 1.

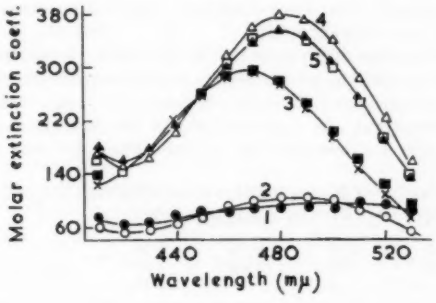


FIG. 2.

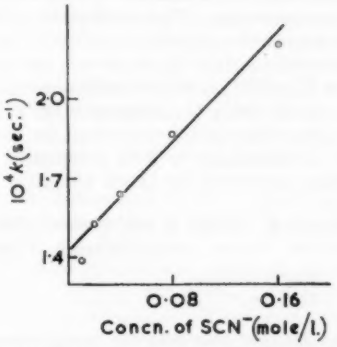


FIG. 1. *Absorption spectra of* 0·001M-*methanolic solutions, acidified by toluene*-p-*sulphonic or perchloric acid.*

(1) *cis*-[Co $en_2(NO_2)Cl]Cl$. (2) *trans*-[Co $en_2(NO_2)Cl]NO_3$. (3) *trans*-[Co $en_2(NO_2)(NCS)]SCN$; ×, *of the crystallised complex*; ■, *of the reaction product of* 0·001M-*trans*-[Co $en_2(NO_2)Cl]NO_3$ *and* 0·04M-KSCN *after a few days.* (4) *cis*-[Co $en_2(NO_2)(NCS)]SCN$. (5) ▲, *of the reaction product of* 0·001M-*cis*-[Co $en_2(NO_2)Cl]Cl$ *and* 0·02—0·08M-KSCN; □, *of the calculated spectrum supposing* 80% *of* cis-[Co $en_2(NO_2)(NCS)]^+$ *and* 20% *of its* trans-*isomer.*

FIG. 2. *The dependence of the pseudo-first-order rate constant of the substitution of chlorine by thiocyanate in* trans-[Co $en_2(NO_2)Cl]^+$ *on the concentration of* SCN^- *at* 30°.

The methanolic solutions of the complexes were acidified by addition of toluene-*p*-sulphonic acid or perchloric acid, to prevent the formation of methoxide ion, which will atack the complex.[5] The water introduced by addition of acids was found to be negligible (0·01%).

The addition of perchloric acid markedly reduced the solubility of the complex. The spectral measurements showed that the addition of only small quantities of these acids, just sufficient to ensure acidity, did not influence their spectra. Larger quantities of toluene-*p*-sulphonic acid added to *trans*-thiocyanatonitrobis(ethylenediamine)cobalt(III) thiocyanate solutions produced a violet colour; the same colour is obtained when *trans*-chloronitrobis-(ethylenediamine)cobalt(III) nitrate, potassium thiocyanate, and a larger quantity of toluene-*p*-sulphonic acid are dissolved in methanol.

A plot of absorption spectra of *trans*- and *cis*-chloronitrobis(ethylenediamine)cobalt(III) ions and *trans*- and *cis*-thiocyanatonitrobis(ethylenediamine)cobalt(III) ions is given in Fig. 1. The absorptions were measured against dry methanol containing the same quantity of the acid as the test solution. The differences in light absorptions of the starting compound and the reaction products are so great that the reaction rate and even the stereochemistry of the products can be determined. It was found that between 400 and 530 mμ the absorption spectrum of

[4] Lund and Bjerrum, *Ber.*, 1931, **64**, 210.
[5] Pearson, Henry, and Basolo, *J. Amer. Chem. Soc.*, 1957, **79**, 5379.

XUM

the freshly prepared 0·001M-solution of *trans*-thiocyanatonitrobis(ethylenediamine)cobalt(III) thiocyanate in methanol was identical with that of the mixture of 0·001M-*trans*-chloronitrobis(ethylenediamine)cobalt(III) nitrate and 0·04M-potassium thiocyanate in methanol after storage for ten half-lives. Fig. 1 (curve 3) contains these results. It is obvious that the replacement of chlorine by thiocyanate in *trans*-chloronitrobis(ethylenediamine)cobalt(III) ion proceeds with complete retention of configuration and that the product is the *trans*-thiocyanatonitro-ion. Basolo *et al.*[6] found for the same substitution in 95% methanol that the substitution proceeds " largely " by retention of configuration.

The greatest difference of absorption between the *trans*-chloro- and the *trans*-thiocyanatonitrobis(ethylenediamine)cobalt(III) ion occurs at 470 mμ where is also the maximum of absorption of the latter ion. This, therefore, was the wavelength used for following the kinetics. The initial concentration of *trans*-chloronitrobis(ethylenediamine)cobalt(III) ion was in all cases 0·001M, and that of potassium thiocyanate was varied between 0·01 and 0·16M. Again, toluene-*p*-sulphonic acid or perchloric acid was used for obtaining acid methanolic solutions. It was found that in the weakly acid solutions the reaction rate was independent of the hydrogen-ion concentration. The methanolic solutions of *trans*-chloronitro- and of *trans*-thiocyanatonitro-bis(ethylenediamine)cobalt(III) ion obeyed the Beer–Lambert law. Therefore the concentration of the latter ion was calculated from the expression $(E - E_0) \times 0{\cdot}001/(E_\infty - E_0)$, where E_0 and E_∞ are the extinctions of the reaction mixture at $t = 0$ and $t = \infty$, respectively. [E_∞ agreed with the extinction of a 0·001M-solution of *trans*-thiocyanatonitrobis(ethylenediamine)cobalt(III) thiocyanate at the same wavelength.] The pseudo-first-order rate constants were calculated up to 50% completion of reaction. In a particular run the first-order rate constant decreased by about 10—20%. Table 1 shows that the pseudo-first-order rate con-

TABLE 1. *Rates of replacement of chlorine by* SCN^- *in* 0·001M-trans-$[Co\ en_2(NO_2)Cl]^+$ *to give* trans-$[Co\ en_2(NO_2)(NCS)]^+$ *in methanol at* 30°.

KSCN (mole/l.)	0·01	0·02	0·04	0·08	0·16
10^4k (sec.$^{-1}$)	1·39	1·53	1·64	1·87	2·20

stants changed also with the initial concentration of potassium thiocyanate. The dependence of the rates on temperature is given in Table 2. From the data of Table 2 a good Arrhenius plot was obtained by the method of least squares, so that the rate constant could be expressed in the form $k = 3{\cdot}44 \times 10^{11} \exp(-21{,}300/\boldsymbol{RT})$ sec.$^{-1}$ over the temperature range studied.

TABLE 2. *Temperature-dependence of the rates of substitution of chlorine by* 0·08M-SCN^- *in* 0·001M-trans-$[Co\ en_2(NO_2)Cl]^+$ *in methanol.*

Temperature	20°	25°	30°	35°
10^3k (sec.$^{-1}$)	5·04	8·41	18·7	26·8

The content of water in methanol was also varied. It was mentioned that absolute methanol contained about 0·05% of water; this was increased to 0·25 and to 0·5%, and the rates of replacement of chlorine by thiocyanate were measured at 30°. The rates remained unchanged. It is therefore most unlikely that water present in absolute methanol takes part in this reaction.

Kinetics and Products of the Reaction of cis-*Chloronitrobis(ethylenediamine)cobalt*(III) *Ion with Thiocyanate Ion in Methanol.*—Ultraviolet light caused partial isomerisation of *cis*-chloronitrobis(ethylenediamine)cobalt(III) ion to its *trans*-isomer, so its methanolic solutions were always kept in the dark. Methanolic solutions were acidified by perchloric acid to a concentration of 0·0001M. The initial concentration of *cis*-chloronitrobis(ethylenediamine)cobalt(III) chloride was always 0·001M. With potassium thiocyanate concentrations of 0·02, 0·04, and 0·08M, at 35·8°, equilibrium was reached in about 4 days.

The absorption spectrum of the reaction product does not correspond to that of either pure *cis*- or pure *trans*-thiocyanatonitrobis(ethylenediamine)cobalt(III) ion but to that of a mixture of the two. The maximum absorption of the *cis*-thiocyanate is at 480 mμ. At that wavelength the extinction coefficients are:

cis-$[Co\ en_2(NO_2)(NCS)]^+$, 380; *trans*-$[Co\ en_2(NO_2)(NCS)]^+$, 275 cm.$^{-1}$ mole^{-1} l.

[6] Basolo, Stone, and Pearson, *J. Amer. Chem. Soc.*, 1953, **75**, 819.

It was shown that at this wavelength, and at the concentrations involved, salts of both these cations obey the Beer–Lambert law, so that concentrations and compositions can be calculated with the aid of the usual linear relations. The molar extinction coefficient of the reaction mixture was found to be 357 cm.$^{-1}$ mole^{-1} l. (arithmetic mean of several measurements at different thiocyanate concentrations); hence the equilibrium mixture contained about 80% of the *cis*- and 20% of the *trans*-ion. (Basolo *et al.*[6] found for the same reaction in 95% methanol "largely" retention of configuration.) For some unknown reason increase of the initial concentration of potassium thiocyanate slightly increased the initial and the final extinctions (E_0 and E_∞) of the reaction mixture. This, however, did not influence the above-mentioned ratio of the *cis*- and *trans*-ions since the differences ($E_\infty - E_0$) remained constant.

The measured absorption spectrum of the reaction products corresponded exactly to the calculated spectrum on the assumption of 80% of *cis*-thiocyanatonitrobis(ethylenediamine)-cobalt(III) ion and 20% of its *trans*-isomer (Fig. 1, curve 5). The first-order rate constants were calculated from the changes of extinctions of the reaction mixtures at 480 mμ. The equation $k = (2{\cdot}303/t)\log_{10}[(E_\infty - E_0)/(E_\infty - E)]$ gave consistent values for the rate constant in every run, and this was independent of the initial concentration of potassium thiocyanate, as shown in Table 3.

TABLE 3. *Rates of replacement of chlorine by* SCN^- *in* 0·001M-cis-$[Co\ en_2(NO_2)Cl]^+$ *to give* 80% *of* cis- *and* 20% of trans-$[Co\ en_2(NO_2)(NCS)]^+$ *in methanol at* 35·8°.

KSCN (mole/l.)	0·02	0·04	0·08
10^5k (sec.$^{-1}$)	1·24, 1·23	1·24, 1·21, 1·27	1·24, 1·24

Measurements were also made at 450 mμ, where the difference of molar extinction coefficients of *cis*-chloronitro- and *cis*-thiocyanatonitro-complexes is much smaller than at 480 mμ, so that the precision of measurements was decreased, but at that wavelength the molar extinction coefficients of *cis*- and *trans*-thiocyanatonitro-complexes are identical so that, regardless of the reaction mechanism, reliable kinetic data could be obtained. It was found that the kinetic data obtained at 480 mμ and at 450 mμ were identical. It is therefore very probable that the replacement of chlorine by thiocyanate gave only the *cis*-product which subsequently underwent isomerisation. Experiments also showed that the *cis*-thiocyanato-nitro-complex—under the conditions of the reaction—slowly isomerised to its *trans*-isomer and in 5 days (time needed for completion of the reaction) 10% of the latter had been formed.

The dependence of the rates on temperature is given in Table 4. The Arrhenius parameters, calculated therefrom by the method of least squares, were 24·6 kcal./mole for the activation energy and $3{\cdot}21 \times 10^{12}$ sec.$^{-1}$ for the frequency factor. The entropy of activation was calculated to be −3·4 e.u.

TABLE 4. *Temperature-dependence of the rates of substitution of chlorine by* 0·04M-SCN^- *in* 0·001M-cis-$[Co\ en_2(NO_2)Cl]^+$ *in methanol.*

Temperature	35·8°	40·1°	45·1°	50·2°
10^5k (sec.$^{-1}$)	1·24	2·12	3·66	7·57

SUMMARY AND DISCUSSION

The main results reported in the preceding section are collected in Table 5 together with the rates of replacement of chlorine in *trans*- and *cis*-dichlorobis(ethylenediamine)-cobalt(III) ions, reported by previous investigators. Although these comparisons of rate constants should be made by using values extrapolated to zero thiocyanate concentration, the inaccuracies involved in such extrapolations would outweigh the advantages gained. We have therefore tried to compare all data at a fixed concentration of thiocyanate.

Table 5 shows that the rate of replacement in *trans*-chloronitrobis(ethylenediamine)-cobalt(III) ion by thiocyanate is 28 times faster than in *trans*-dichlorobis(ethylenediamine)-cobalt(III) ion (calculated for one chlorine atom). If the S_N1 mechanism operated one would expect slower reaction in the *trans*-chloronitro- than in the *trans*-dichloro-complex because the polarisation of the cobalt atom, caused by the nitro-group, should oppose heterolysis, as discussed in the first section. Table 6 contains the rates of aquation of the

same complexes. It can be seen that very similar ratios of rates to those in the replacements by thiocyanate are obtained in the aquations (see Table 6).

TABLE 5. *Rates of replacement of chlorine in bis(ethylenediamine)cobalt*(III) *ions by* SCN^- *in methanol.*

Co en_2 complex	Co en_2 complex (M)	SCN^- (M)	10^5k (sec.$^{-1}$) 25°	35·8°	Note
trans-[Co $en_2(NO_2)Cl]^+$	0·001	0·08	8·41		
cis-[Co $en_2(NO_2)Cl]^+$	0·001	0·08	0·29 *	1·24	
trans-[Co $en_2Cl_2]^+$	0·001—0·002	0·08	0·30		*a*
cis-[Co $en_2Cl_2]^+$	0·0007	0·05	1·82 †		*b*

* Pearson, Henry, and Basolo's data [5] have been halved since the displacement of one chlorine is required for comparison with the other rate figures in Tables 5 and 6. [b] Brown and Ingold's data have also been halved.

* Calc. from the rate at 35·8° and the activation energy of 24·6 kcal./mole.

† Calc. from the rate at 35·8° and the assumed activation energy of 22·0 kcal./mole.

TABLE 6. *Rates of aquation in bisethylenediaminecobalt*(III) *complexes at* 25°.

Complex	10^5k (sec.$^{-1}$)	Mechanism suggested	Note
trans-[Co $en_2(NO_2)Cl]^+$	81·85	S_N2	*a*
cis-[Co $en_2(NO_2)Cl]^+$	11·0	S_N2	*b*
trans-[Co $en_2Cl_2]^+$	3·16	S_N1	*c*
cis-[Co $en_2Cl_2]^+$	14·0	S_N1	*d*

* Calc. from the rate at 30° and the activation energy of 21·5 kcal./mole reported by Ašperger and Ingold.[3] [b] Calc. from the rate at 30° and the activation energy of 22·35 kcal./mole reported by Ašperger and Ingold.[3] [c] Rate data by Mathieu [7] at 30° have been multiplied by 2·303 and halved, since the displacement of one chlorine is required for comparison with the other rate figures in the Table. In calculation of the rate, the activation energy of 24·2 kcal./mole was used, as given by Mathieu. [d] Rate data by Mathieu [7] have been multiplied by 2·303 and halved.

Ratios of rates of substitution of chlorine by SCN^- *in methanol at* 25°:

(*a*) k for *trans*-[Co $en_2(NO_2)Cl]^+/k$ for *trans*-[Co $en_2Cl_2]^+$ $\simeq\simeq$ 28
(*b*) k for *cis*-[Co $en_2(NO_2)Cl]^+/k$ for *cis*-[Co $en_2Cl_2]^+$ $\simeq$ 0·16

Ratios of rates of aquations at 25°:

(*a*) k for *trans*-[Co $en_2(NO_2)Cl]^+/k$ for *trans*-[Co $en_2Cl]^+$ $\simeq\simeq$ 26
(*b*) k for *cis*-[Co $en_2(NO_2)Cl]^+/k$ for *cis*-[Co $en_2Cl_2]^+$ $\simeq$ 0·8

The ratios of rates of replacement of chlorine by thiocyanate in the *trans*- and *cis*-chloronitro-complexes and *trans*- and *cis*-dichloro-complexes are also similar to the ratios of the rates of aquations of the same complexes.

Ratios of rates of replacement of chlorine by SCN^- *in methanol at* 25°.

(*a*) k for *trans*-[Co $en_2(NO_2)Cl]^+/k$ for *cis*-[Co $en_2(NO_2)Cl]^+$ $\simeq$ 29
(*b*) k for *trans*-[Co $en_2(Cl_2)]^+/k$ for *cis*-[Co $en_2Cl_2]^+$ $\simeq$ 0·17

Ratios of rates of the aquations at 25°:

(*a*) k for *trans*-[Co $en_2(NO_2)Cl]^+/k$ for *cis*-[Co $en_2(NO_2)Cl]^+$ $\simeq$ 7·4
(*b*) k for *trans*-[Co $en_2Cl_2]^+/k$ for *cis*-[Co $en_2Cl_2]^+$ $\simeq$ 0·23

The accelerating influence of the nitro-group and the above-mentioned similarities of the rate ratios for the reaction with thiocyanate in methanol and the solvolytic aquation lead us to believe that the rate-determining step in the replacement of chlorine by thiocyanate in the *trans*- (and possibly *cis*-) chloronitrobis(ethylenediamine)cobalt(III) cation is a bimolecular methanolysis, which is followed by a fast replacement of co-ordinated methanol by thiocyanate. The equilibrium of the reaction (1) is shifted very much towards the chloronitro-complex:

$$\textit{trans}\text{-[Co en}_2(NO_2)Cl]^+ + CH_3{\cdot}OH \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \textit{trans}\text{-[Co en}_2(NO_2)(CH_3{\cdot}OH)]^{++} + Cl^- \quad (1)$$

[7] Mathieu, *Bull. Soc. chim. France*, 1936, **3**, 2152.

Therefore the absorption spectra of the methanolic solutions of this complex are unchanged. In the presence of the thiocyanate ions reactions (2) and (3) take place:

$$trans\text{-}[Co\ en_2(NO_2)(CH_3{\cdot}OH)]^{++} + SCN^- \xrightarrow{k_2} trans\text{-}[Co\ en_2(NO_2)(NCS)]^+ + CH_3{\cdot}OH \quad . \quad (2)$$

$$trans\text{-}[Co\ en_2(NO_2)Cl]^+ + SCN^- \xrightarrow{k_3} trans\text{-}[Co\ en_2(NO_2)(NCS)]^+ + Cl^- \quad . \quad (3)$$

The rate constant k_2 must be greater than k_1. The rate of formation of the *trans*-$[Co\ en_2(NO_2)(NCS)]^+$ ion is given by:

$$\text{Rate} = \{k_1' + k_3[SCN^-]\}[trans\text{-}[Co\ en_2(NO_2)Cl^+] \quad . \quad . \quad . \quad (4)$$

$k_1' + k_3[SCN^-]$ is equal to the pseudo-first-order rate constant k determined experimentally. In Fig. 2 the values of k from Table 1 are plotted as a function of the thiocyanate concentration. The straight line enabled a rough determination of k_1' (intercept) and k_3 (slope); k_1' was found to be $1{\cdot}42 \times 10^{-4}$ sec.$^{-1}$ and k_3 to be $5{\cdot}2 \times 10^{-4}$ sec.$^{-1}$ mole^{-1} l. The increase of the thiocyanate concentration makes the S_N2 substitution of chlorine increasingly important; *e.g.*, when the thiocyanate was 0·04M (40-fold excess), k was $1{\cdot}6 \times 10^{-4}$ sec.$^{-1}$. It follows that 13% of the product was formed by S_N2 substitution of chlorine by the thiocyanate ion and 87% *via* methanolysis.

The accelerating influence of the nitro-group can now be understood. The rate-determining step in the substitution by the thiocyanate ion is the methanolysis, which occurs as an S_N2 reaction; S_N2 reactions are in general less sensitive to electron-displacement than S_N1 reactions, since the release of electrons towards the reaction centre assists bond breaking and thus makes the bond formation more difficult. Since methanol is a weak nucleophilic reagent it needs help from polarisation to be brought into reaction. Therefore the polarisation demand of the binding of the methanol is more important than the loosening of the displaced chlorine. This is analogous to the influence of the nitro-group in aquation of the *trans*-chloronitrobis(ethylenediamine)cobalt(III) ion studied by Ašperger and Ingold.[2] They suggested that 4*d*-orbitals of cobalt play an intermediate rôle in the binding of water, which is greatly assisted when the underlying 3*d*-shell is pulled out of the way by the nitro-substituent. It seems very likely that the 4*d*-orbitals of cobalt also play an intermediate rôle in the binding of methanol. The rate of exchange of *cis*- and *trans*-chloronitrobis(ethylenediamine)cobalt(III) ion with radioactive chlorine is now being studied and compared with the rate of isomerisation in order to obtain more accurate information about the mechanism and steric course of these reactions.

It should be pointed out that the first-order kinetic form observed for the weakly nucleophilic reagents could arise from a rate-determining methanolysis followed by a fast replacement of co-ordinated methanol by the reagent. This would only be a serious objection to Brown and Ingold's mechanism if the methanolysis were bimolecular. Comparison of methanolysis with aquation, however, would lead us to believe that the methanolysis of *cis*- and *trans*-dichlorobis(ethylenediamine)cobalt(III) ion is unimolecular and that the reactive $[Co\ en_2Cl(MeOH)]^{2+}$ appears only because the methanol is suitably placed to occupy the position vacated.

Experimental

Preparations.—*trans*-Chloronitrobis(ethylenediamine)cobalt(III) nitrate and the chloride of the *cis*-isomer were used from a stock previously prepared.[3] *trans*- and *cis*-Thiocyanatonitrobis(ethylenediamine)cobalt(III) thiocyanates were prepared by Werner's method [5] (Found: ionic SCN^-, 17·03 in *trans*- and 16·85% in *cis*-$[Co\ en_2(NO_2)(NCS)]SCN$. Calc.: 17·02%).

Reagent-grade absolute methanol was further dehydrated by Lund and Bjerrum's method.[4]

[5] Gmelin's "Handbuch der anorganischen Chemie," No. 58, Berlin, 1930, p. 270.

XUM

Analyses by the Karl Fischer method showed that the dried methanol contained about 0·05% of water.

Spectroscopy.—Light-absorption intensity measurements were made with a Hilger H 700 quartz spectrophotometer and 10 mm. cells.

Kinetics.—The methanol was acidified by toluene-*p*-sulphonic acid or 60% perchloric acid. 0·001M-Solutions of the chloronitro-complexes were prepared by short warming or by prolonged shaking at room temperature. The solutions were always kept in the dark to prevent isomerisation. The solution of the complex was thermally equilibrated in a water thermostat (±0·01°) and a weighed quantity of dried sodium thiocyanate was added, which dissolved readily.

The authors are indebted to Sir Christopher Ingold and Dr. Martin Tobe for helpful discussions.

Department of Physical Chemistry,
Institute "Rudjer Bošković" Zagreb.
Department of Inorganic and Physical Chemistry,
Faculty of Pharmacy, University of Zagreb,
Zagreb, Croatia, Yugoslavia.

[*Received, November 7th,* 1960.]

---

408. *Derivatives of Benzo-1,4-dioxan. Part V.**

By P. M. Heertjes and H. C. A. van Beek.

The behaviour of some polynitrobenzo-1,4-dioxan compounds, especially their reactivity towards alcoholic ammonia, is reported.

It is known that aromatic polynitro-compounds can be converted by ammonia into amino-nitro-compounds. Because this could be a convenient method for preparing amino-nitro-derivatives of benzo-1,4-dioxan, which are used in the preparation of azo-dyes, the ammonolysis of some polynitrobenzo-1,4-dioxan compounds was investigated. The reactions to be described are represented in the annexed chart.

6,7-Dinitrobenzo-1,4-dioxan [1] (I) is unchanged during 3 hr. by an excess of ammonia in ethanol at 130°; under milder conditions 5,6,7-trinitrobenzo-1,4-dioxan (III) is converted by ammonia into amino-nitro-compounds (see below). Crude 6,7-dinitrobenzo-1,4-dioxan is usually contaminated with 5,6,7-trinitrobenzo-1,4-dioxan (III), from which it is difficult to separate it by crystallisation, and treatment with alcoholic ammonia proved a convenient method for the purification of the former.

The preparation of 6-amino-7-nitrobenzo-1,4-dioxan has been described elsewhere.[2] Reduction of 6,7-dinitrobenzo-1,4-dioxan (I) to 6,7-diaminobenzo-1,4-dioxan (II) and preparation of the mono- and di-acetyl derivatives of the amine are given in this paper. The condensation product of 6,7-diaminobenzo-1,4-dioxan with 9,10-phenanthraquinone was obtained by Robinson and Robinson [3] who, however, did not describe the free diamine.

The reaction of 5,6,7-trinitrobenzo-1,4-dioxan [1] (III) with ammonia was also studied by Robinson and Robinson [3] who isolated and identified two of the three products obtained by us. It has been found that when 5,6,7-trinitrobenzo-1,4-dioxan (III) is treated with an amount of ammonia sufficient to replace only one nitro-group, mainly 6-amino-5,7-dinitrobenzo-1,4-dioxan (IV) is formed. The structure was established by deamination of this compound to 5,7-dinitrobenzo-1,4-dioxan.[4] The crude product also contains a small quantity of the known 5-amino-6,7-dinitrobenzo-1,4-dioxan [3] (VI).

6-Amino-5,7-dinitrobenzo-1,4-dioxan (IV) was converted by an excess of ammonia in

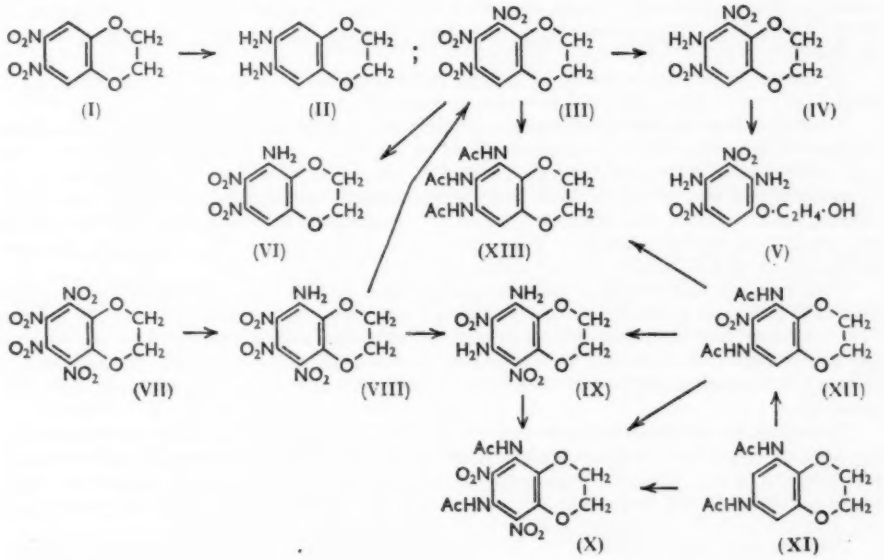
* Parts I—IV, *J.*, 1954, 18, 1868; 1955, 1313; 1957, 3445.

[1] Heertjes, Dahmen, and Wierda, *Rec. Trav. chim.*, 1941, **60**, 569.
[2] Heertjes and Revallier, *Rec. Trav. chim.*, 1950, **69**, 262.
[3] G. M. Robinson and R. Robinson, *J.*, 1917, **111**, 929.
[4] Heertjes, Knape, and Talsma, *J.*, 1954, 1868.

XUM

ethanol into 2,4-diamino-3,5-dinitrophenyl 2-hydroxyethyl ether (V) which had previously [3] been obtained directly from the trinitro-compound.

5,6,7,8-Tetranitrobenzo-1,4-dioxan [1] (VII) was converted in ethanol into 5-amino-6,7,8-trinitrobenzo-1,4-dioxan (VIII) by an amount of ammonia sufficient to replace only one nitro-group. No other monoamino-trinitro-compound was isolated. The structure of



the monoamino-compound was established by deamination to 5,6,7-trinitrobenzo-1,4-dioxan (III). With an amount of ammonia sufficient to replace two of the four nitro-groups 5,6,7,8-tetranitrobenzo-1,4-dioxan (VII) gave 5,7-diamino-6,8-dinitrobenzo-1,4-dioxan (IX). The structure of this compound followed from the identification of its diacetyl derivative with 5,7-diacetamido-6,8-dinitrobenzo-1,4-dioxan (X) obtained by nitration of 5,7-diacetamidobenzo-1,4-dioxan [4] (XI) with nitric acid (*d* 1·52). The 6-nitro-derivative of 5,7-diacetamidobenzo-1,4-dioxan (XII) is obtained if the nitration is carried out with nitric acid (*d* 1·4). The 6-position of the nitro-group follows from conversion of the 5,7-diacetamido-mononitrobenzo-1,4-dioxan into a triacetamidobenzo-1,4-dioxan which appeared to be identical with 5,6,7-triacetamidobenzo-1,4-dioxan (XIII) obtained by reduction of 5,6,7-trinitrobenzo-1,4-dioxan and acetylation of the resulting triamino-compound.

Experimental

M. p.s are corrected.

6,7-*Diaminobenzo*-1,4-*dioxan* (II).—Granulated tin (22·5 g.) was added to a suspension of 6,7-dinitrobenzo-1,4-dioxan (I) (11·5 g.) in hydrochloric acid (*d* 1·19; 40 ml.). The mixture was heated at 80° for 60 min. The clear solution obtained was made alkaline with sodium hydroxide (40 g.) in water (200 ml.). The resulting suspension was extracted with benzene. The extract was dried and the benzene was distilled off under reduced pressure with exclusion of oxygen. 6,7-*Diaminobenzo*-1,4-*dioxan* was obtained and, recrystallised from benzene, had m. p. 122—123° (3·5 g., 35·7%) (Found: N, 16·9. $C_8H_{10}N_2O_2$ requires N, 16·9%).

The mono- and di-acetyl derivatives were obtained by use of acetic anhydride in benzene.

To prepare the monoacetyl derivative a dilute solution of acetic anhydride in benzene was added slowly to a solution of the diamine in benzene at 60°. Crystallisation gave 6-acetamido-7-amino-, m. p. 130—131° (from benzene), and 6,7-diacetamido-benzo-1,4-dioxan, m. p. 241° (decomp.) (from acetic acid).

6-*Amino*-5,7-*dinitrobenzo*-1,4-*dioxan* (IV).—To a suspension of 5,6,7-trinitrobenzo-1,4-dioxan (III) (10 g.) in boiling ethanol (300 ml.), ammonia (5·8 ml.; *d* 0·905) in ethanol (30 ml.) was added in 3 hr. A red solution was formed. On cooling, orange needles of 6-*amino*-5,7-*dinitrobenzo*-1,4-*dioxan* separated. These were filtered off and crystallised from 1 : 1 acetone–water (yield, 4·5 g., 51%), then having m. p. 164—165° (Found: N, 17·4, 17·5. $C_8H_7N_3O_6$ requires N, 17·4%).

In the crude product a small amount of yellow crystals of 5-amino-6,7-dinitrobenzo-1,4-dioxan (VI), m. p. 202—203°, was present and was separated.

A suspension of the aminodinitrobenzo-1,4-dioxan (1·5 g.) in acetic acid (100 ml.) was added dropwise to a solution of sodium nitrite (2 g.) in sulphuric acid (45 ml., *d* 1·84) at 0°. The mixture was stirred for 1 hr. and then added to a solution of sodium hypophosphite (5 g.) in 10N-sulphuric acid (20 ml.). After being kept overnight the mixture was diluted with water (200 ml.) and extracted with ether (3 × 30 ml.). The extracts were evaporated and the residue was crystallised several times from dilute acetic acid. It had m. p. 141—143°, not depressed on admixture with 5,7-dinitrobenzo-1,4-dioxan.

2,4-*Diamino*-3,5-*dinitrophenyl* 2-*Hydroxyethyl Ether* (V).—6-Amino-5,7-dinitrobenzo-1,4-dioxan (IV) (0·5 g.) in ethanol (15 ml.) was refluxed with aqueous ammonia (0·5 ml.; *d* 0·905) for 1 hr. After cooling, the precipitate was filtered off, extracted several times with boiling acetone, and recrystallised from acetic acid. It had m. p. 240—241° alone or mixed with the product obtained by treating 5,6,7-trinitrobenzo-1,4-dioxan with ammonia in ethanol as described in ref. 3.

5-*Amino*-6,7,8-*trinitrobenzo*-1,4-*dioxan* (VIII).—To a suspension of 5,6,7,8-tetranitrobenzo-1,4-dioxan (VII) (10 g.) in boiling ethanol (300 ml.) 0·5N-ethanolic ammonia (126 ml.) was added during 1½ hr. The resulting solution was filtered hot and then cooled. The crude *monoamine* crystallised and was filtered off (3 g., 30%). Recrystallised from acetone–ethanol (1 : 1), it had m. p. 224·5° (Found: N, 19·3. $C_8H_6N_4O_8$ requires N, 19·6%).

The structure was established by diazotising the substance (1·1 g.) in acetic acid (30 ml.) with sodium nitrite (0·95 g.) in sulphuric acid (10 ml.; *d* 1·84) at 10—15°. The mixture was stirred for 2 hr., then added dropwise to boiling ethanol (40 ml.) in 10 min., refluxed for ½ hr., and poured on ice. The precipitated 5,6,7-trinitrobenzo-1,4-dioxan, when crystallised from acetone, had m. p. and mixed m. p. 154—155°.

5,7-*Diamino*-6,8-*dinitrobenzo*-1,4-*dioxan* (IX).—A stream of dry ammonia (100 ml./min.) was passed through a suspension of 5,6,7,8-tetranitrobenzo-1,4-dioxan (VII) (10 g.) in boiling ethanol (500 ml.) for 30 min. A red solution was first formed and then orange 5,7-*diamino*-6,8-*dinitrobenzo*-1,4-*dioxan* separated. After cooling, the precipitate was filtered off and crystallised from ethanol (yield 6 g., 72%; m. p. 262—263°) (Found: N, 21·9. $C_8H_8N_4O_6$ requires N, 21·9%).

With acetic anhydride and a drop of concentrated sulphuric acid, this amine gave its *diacetyl derivative* (XIII), m. p. 284·0—284·8° (from ethanol) (Found: C, 42·6; H, 4·0; N, 16·1. $C_{12}H_{12}N_4O_8$ requires C, 42·4; H, 3·6; N, 16·4%).

When 5,7-diacetamidobenzo-1,4-dioxan (XI) (2 g.) was added in portions to stirred nitric acid (30 ml.; *d* 1·52) at −10° and the mixture was stirred for a further 10 min. and then poured on ice, the precipitate (1·5 g., 43%), m. p. 282—284° (from ethanol), did not depress the m. p. of the last-mentioned diacetyl derivative.

5,7-*Diacetamido*-6-*nitrobenzo*-1,4-*dioxan* (XII).—5,7-Diacetamidobenzo-1,4-dioxan (2 g.) was nitrated as just described but with 30 ml. of nitric acid (*d* 1·40). The *mononitro-compound*, when crystallised from ethanol, had m. p. 261—262° (1·2 g., 50%) (Found: C, 49·0; H, 4·5; N, 14·4. $C_{12}H_{13}N_3O_8$ requires C, 48·8; H, 4·4; N, 14·2%).

5,6,7-*Triacetamidobenzo*-1,4-*dioxan* (XIII).—5,6,7-Trinitrobenzo-1,4-dioxan (8 g.) in ethanol (500 ml.) was hydrogenated in presence of Raney nickel with the theoretical amount of hydrogen. After filtration, the alcohol was distilled under reduced pressure in absence of oxygen. The residue was treated with an excess of acetic anhydride, and later diluted with water. The precipitated 5,6,7-*triacetamidobenzo*-1,4-*dioxan* recrystallised from ethanol–water (2 : 1), then having m. p. 280—282° (4 g., 44%) (Found: C, 54·9; H, 5·7; N, 13·8. $C_{14}H_{17}N_3O_5$ requires C, 54·7; H, 5·5; N, 13·7%).

XUM

Hydrogenation (Raney nickel) of the nitration product (HNO_3, d 1·40) of 5,7-diacetamidobenzo-1,4-dioxan (XI) and subsequent acetylation gave 5,6,7-triacetamidobenzo-1,4-dioxan, m. p. and mixed m. p. 280—282°.

LABORATORY OF CHEMICAL TECHNOLOGY,
TECHNICAL UNIVERSITY, DELFT, HOLLAND. [*Received, December 5th*, 1960.]

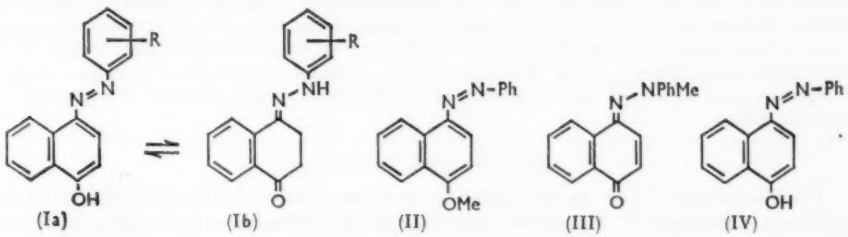
---

409. *Infrared Spectra and Structure of Arylazonaphthols.*

By K. J. MORGAN.

Infrared spectra show the presence of an azo–hydrazone tautomerism (*e.g.*, Ia ⇌ Ib) both in the solid and in solutions of 1-arylazo-2-naphthols and 4-arylazo-1-naphthols. The position of equilibrium moves towards the hydrazone in polar solvents and under the influence of electron-withdrawing substituents in the aryl group.

THE structure of the compounds formed by condensation of diazonium salts with phenols has provoked many investigations. Chemical evidence [1] has been used to support the formulation of the products as hydroxyazo-compounds (*e.g.*, Ia) and as hydrazones (*e.g.*, Ib). More valid evidence is provided by physical properties, notably of their electronic spectra. Strong presumptive evidence for the presence of tautomerism in the hydroxyazo-compounds was first provided by Kuhn and Bär.[2] The ultraviolet spectrum of 4-phenylazo-1-naphthol * (I; R = H) shows bands at 410 and 460 mμ which correspond in position to bands found in the *O*-methyl (II) and *N*-methyl derivative (III), respectively. The relative intensity of the bands in the spectrum of the parent compound changes with solvent, and in the more polar solvents (acetic acid, nitrobenzene) only the longer-wavelength band is seen. Similar effects have been detected in the ultraviolet spectra of substituted 4-phenylazo-1-naphthols.[3,4] 1-Phenylazo-2-naphthol and the isomeric 2-phenylazo-1-naphthol show analogous effects.[5]



The existence of an equilibrium in the solutions of the azonaphthols is clearly demonstrated [5] by the formation of an isosbestic point by the spectral curves measured in a variety of solvents. Kuhn and Bär [2] suggested that this equilibrium was that of a keto–enol tautomerism (Ia ⇌ Ib) and subsequent work [3-8] has supported this conclusion. Despite the loss of a fully aromatic ring in the hydrazone, the total bond energies of the

* The designation "arylazonaphthol" is used throughout this paper for convenience; it is not intended to define the structure of the compound.

[1] See, *e.g.*, (*a*) McPherson, *Amer. Chem. J.*, 1899, **22**, 364; (*b*) Fierz-David, Blangey, and Streiff, *Helv. Chim. Acta*, 1946, **29**, 1718.
[2] Kuhn and Bär, *Annalen*, 1935, **516**, 143.
[3] Burawoy and Thompson, *J.*, 1953, 1443.
[4] Shingu, *Sci. Papers Inst. Phys. Chem. Res.* (*Tokyo*), 1938, **35**, 78.
[5] Burawoy, Salem, and Thompson, *J.*, 1952, 4793.
[6] Ospenson, *Acta Chem. Scand.*, 1951, **5**, 491.
[7] Sawicki, *J. Org. Chem.*, 1957, **22**, 743.
[8] Badger and Buttery, *J.*, 1956, 614.

XUM

two forms are comparable [6] and from recent results [9] it follows that the hydrazone (Ib; R = H) cannot be destabilised relative to the azo-form by more than 2 kcal./mole. It has recently [9,10] been shown that the existence of *cis*-4-phenylazo-1-naphthol (IV) is too transient at room temperatures to permit any possibility that the tautomerism involves a *cis–trans*-conversion about the azo-link. No evidence for a tautomeric equilibrium is found in the spectra of hydroxyazobenzenes or hydroxyazoanthracenes: the former behave spectrally as phenolic compounds,[11] the latter as hydrazones.[4,6]

Investigation of the infrared spectra of hydroxyazo-compounds, which can in principle provide direct evidence of the structure, has been restricted to some isolated spectra [12-15] and to a more detailed examination of the phenylazonaphthols as solids.[16] A more complete examination of the infrared spectra appeared desirable; accordingly, spectra of 4-phenylazo-1-naphthols and 1-phenylazo-2-naphthols substituted in the phenyl ring have been measured.

Experimental

Azo compounds were prepared by the usual diazo-coupling reactions with α- and β-naphthols and were purified chromatographically and by crystallisation to constant m. p. The following m. p. were observed: 4-arylazo-1-naphthols (I), R = H, 208°; *o*-MeO, 177—178°; *m*-MeO, 159°; *p*-MeO, 173°; *o*-Me, 162—163°; *m*-Me, 200°; *p*-Me, 211·5°; *o*-Cl, 189·5—190·5°; *m*-Cl, 227·5—228° (decomp.); *p*-Cl, 229·5° (decomp.); *o*-NO_2, 256—257°; *m*-NO_2, 242—242·5° (decomp.); *p*-NO_2, 281—282° (decomp.); 1-arylazo-2-naphthols (VII), R = H, 133—134°; *o*-MeO, 187—188°; *m*-MeO, 149°; *p*-MeO, 142°; *o*-Me, 132—133°; *m*-Me, 141—142°; *p*-Me, 133—134°; *o*-Cl, 171—173°; *m*-Cl, 164—165°; *p*-Cl, 165—166°; *o*-NO_2, 217—219°; *m*-NO_2, 197—198°; *p*-NO_2, 259—260°. These values agree with those in the literature.

1-Methoxy-4-phenylazonaphthalene, m. p. 80°, was prepared by methylation of the naphthol; [17] 1,4-naphthaquinone methylphenylhydrazone, m. p. 121—122°, was prepared from the quinone with methylphenylhydrazine.[1]

Spectra of the solids were obtained from mulls with Nujol and Fluorolube and from discs with potassium bromide; no significant differences could be detected between the spectra of the mulls and of the discs. Spectra of solutions were determined at sufficient dilution (0·005—0·007M) to be free from intermolecular hydrogen-bonding.[18] The low solubility of some compounds, notably the derivatives of α-naphthol, entailed the use of lower concentrations, and several compounds proved insufficiently soluble in the less polar solvents to yield useful spectra. Bromoform containing 4% (w/w) ethanol was used; other solvents were of " Spectro " grade.

Spectra were measured with a Perkin-Elmer Model 21 spectrophotometer equipped with rock-salt optics.

Results and Discussion

The infrared spectra of the tauomeric forms of the hydroxyazo-compounds should show significant differences.[19] Bands characteristic of the hydroxyl and azo-groupings should appear in the spectrum of the azo-form and be replaced by amino- and carbonyl bands in the spectrum of the hydrazone. Changes in the position of the tautomeric equilibrium should be accompanied by changes in the intensity of these bands. Some characteristic hydroxy-, amino-, and carbonyl-band frequencies and apparent extinction coefficients are given in the accompanying Tables. [The extinction coefficient, ϵ_ν^α, is defined by $\epsilon_\nu^\alpha = (1/cl)\ (\log T_0/T)_\nu$ and is not corrected for the use of finite slit widths.]

[9] Fischer and Frei, *J.*, 1959, 3159.
[10] Brode, Gould, and Wyman, *J. Amer. Chem. Soc.*, 1952, **74**, 4641; 1953, **75**, 1856.
[11] Burawoy and Chamberlain, *J.*, 1952, 3734.
[12] Druckrey, Schmähl, and Dannenberg, *Naturwiss.*, 1952, **39**, 393.
[13] Le Fèvre, O'Dwyer, and Werner, *Austral. J. Chem.*, 1953, **6**, 341.
[14] Kendall, *Analyt. Chem.*, 1953, **25**, 382.
[15] Dolinsky and Jones, *J. Assoc. Offic. Agric. Chemists*, 1954, **37**, 197.
[16] Hadži, *J.*, 1956, 2143.
[17] Charrier and Casale, *Gazzetta*, 1914, **44**, 228.
[18] Putnam, *J.*, 1960, 487.
[19] Cf. Tanner, *Spectrochim. Acta*, 1959, **15**, 20.

XUM

The apparent half band width ($\Delta\nu_{\frac{1}{2}}$) (width at half-peak absorbance) of all the bands listed increases with the polarity of the solvent. In these circumstances the extinction coefficient provides a poor estimate of the intensity of the absorption, and in the present case the triangular area, $t = 10^{-3}\varepsilon^{\alpha} . \Delta\nu_{\frac{1}{2}}^{\alpha}$, is a more useful, if approximate, measure of the band intensity as it takes account of the variation in band width; values of t are listed in the Tables. Similar expressions have been proposed [20] for the calculation of true band intensities.

An attempt was made to locate in the spectra characteristic bands other than those listed in the Tables; this was to some extent hampered by the opacity of the solvents over much of the spectral range. Typical aromatic bands and C–H deformation bands characteristic of the various substitution patterns were observed.[21] Hadži [16] assigned bands near 1250 and 1540 cm.$^{-1}$ in the spectra of the phenylazonaphthols to in-plane

TABLE 1. *Hydroxyl and amino-stretching bands in the spectra of* 4-*arylazo*-1-*naphthols.*

Substituent R in (I)		Amino (N–H) bands						Hydroxyl (O–H) bands				
		Solid	C_6H_{12}	C_2Cl_4	CCl_4	CH_2Cl_2	$CHCl_3$	C_6H_{12}	C_2Cl_4	CCl_4	CH_2Cl_2	$CHCl_3$
H		3140	—	—	—	3360	3360	—	—	—	3580	3570
		3260				40	45				90	70
	t					—	—				3·2	—
o-MeO		3320	3380	3370	3370	3350	3340	0	0	0	0	0
			75	95	110	130	130					
	t		1·8	2·4	2·7	4·0	4·2					
m-MeO		3130	—	—	—	3350	3350	—	—	—	3560	3560
		3250				55	55				60	45
	t					2·3	—				2·6	—
p-MeO		3130	—	—	—	3340	3340	—	—	—	3575	3570
		3250				30	35				105	105
	t					—	—				5·8	—
o-Me		3300	0	0	3380	3360	3360	3610	3610	3600	3570	3570
		3240			30	40	40	145	110	108	70	65
	t				0·7	—	—	3·6	3·3	3·2	3·1	—
m-Me		3140	—	—	—	3340	3340	—	—	—	3580	3575
		3250				40	45				80	60
	t					1·4	—				3·2	—
p-Me		3140	—	—	—	3350	3350	—	—	—	3580	3570
		3270				40	40				85	70
	t					1·6	—				3·2	—
o-Cl		3340	3370	3370	3370	3350	3340	0	0	0	0	0
			55	105	105	75	70					
	t		1·4	2·1	2·1	2·6	2·8					
m-Cl		3280	—	—	—	3350	3340	—	—	—	3580	3570
						50	55				60	25
	t					2·3	—				1·5	—
p-Cl		3220	—	—	—	—	—	—	—	—	—	—
		3170										
o-NO_2		3320	—	3330	—	3320	3300	—	0	—	0	0
				120		115	90					
	t			3·0		3·4	3·4					
m-NO_2		3280	—	—	—	—	3330	—	—	—	—	0
							75					
	t						—					
p-NO_2		3280	—	—	—	—	—	—	—	—	—	—

bending modes of the hydroxyl and amino-group; similar bands were detected but proved of little diagnostic value. A band near 1450 cm.$^{-1}$ in the spectrum of many azo-compounds has been assigned [13,22] to the –N=N– stretching frequency; comparison of the spectra of the *N*-methyl (III) and *O*-methyl (II) compounds showed that the latter contained a very

[20] Fox and Martin, *Proc. Roy. Soc.*, 1938, *A*, **167**, 257; Ramsay, *J. Amer. Chem. Soc.*, 1952, **74**, 72.
[21] Randle and Whiffen, "Molecular Spectroscopy," Institute of Petroleum, 1954, p. 111; Hawkins, Ward, and Whiffen, *Spectrochim. Acta*, 1957, **10**, 105.
[22] Le Fèvre, Sousa, and Werner, *Austral. J. Chem.*, 1956, **9**, 151; Le Fèvre and Werner, *ibid.*, 1957, **10**, 26.

XUM

weak band at 1445 cm.$^{-1}$ not found in the former. Similar bands occur in the spectra of the *p*-hydroxyazobenzene and of many of the arylazonaphthols; in all cases they are weak and no significant changes in intensity could be detected.

4-Arylazo-1-naphthols.—The infrared spectrum of solid 4-phenylazo-1-naphthol shows bands in the single-bond stretching region at 3140 and 3260 cm.$^{-1}$. In spectra of solutions these are replaced by bands near 3360 and 3580 cm.$^{-1}$ which may best be ascribed to N–H and O–H stretching frequencies.[23] Similar bands are found in the spectra of a number of substituted derivatives (Table 1) and establish the presence of a tautomeric mixture both in solution and in the solid. The intensity of the bands varies both with solvent and with the substituent carried by the phenyl group. In general the intensity of the amino-band increases and that of the hydroxyl band decreases as the polarity of the solvent is increased. Further, the presence of electron-withdrawing groups on the phenyl ring increases the intensity of the amino-band at the expense of the hydroxyl band. This effect will be discussed in more detail below.

The spectrum of solid 4-phenylazo-1-naphthol shows only one band near the carbonyl stretching region, at 1625 cm.$^{-1}$. This frequency is low: benzophenone and anthrone [24] absorb at 1650 cm.$^{-1}$, and 1,4-naphthaquinone at 1664 cm.$^{-1}$. However, the carbonyl band in the spectrum of the *N*-methyl derivative (III) appears at 1632 cm.$^{-1}$, and consequently the band in the spectrum of the parent compound can confidently be ascribed to a carbonyl vibration. The low frequencies of these bands must be due in part to the electron-releasing character of the hydrazone group, and in part to intermolecular interactions. Low values have also been reported [24] for 2-amino-anthraquinones and related compounds. Similar bands appear in the spectra of the phenyl-substituted derivatives (Table 2) and confirm the presence of the hydrazone tautomer in the solid state. No such band is found in the spectrum of the *O*-methyl derivative (II).

In solution the band moves to higher frequencies (Table 2). The position is dependent both on solvent and on substituent: higher frequencies are shown in the less polar solvents and by compounds containing electron-withdrawing substituents. The quantitative dependence of the frequency on the electron-withdrawing ability of the substituent can be seen in the linear variation of frequency with the Hammett substitution constant (σ) (Fig. 1). The displacement of the band by solvents is that typical of a carbonyl band.[25] The correlation of these shifts has been systematised by Bellamy *et al.*[26] by plotting relative frequency shifts ($\Delta\nu/\nu$) against those of a standard compound. Similar plots for those 4-arylazo-1-naphthols yielding sufficient data, with the *N*-methyl compound (III) as standard, are essentially linear (Fig. 2): this further substantiates the assignment of this band to a carbonyl stretching frequency and so confirms the presence of the hydrazone tautomer.

The intensity of the carbonyl absorption also varies with both solvent and substituent. In the more polar solvents the intensity of the band increases. (Examination of the extinction coefficients does not reveal this: the apparent band width increases faster than the band intensity, and the extinction coefficients actually decrease.) A similar increase in intensity is found in the carbonyl band of the *N*-methyl compound but the ratio $t_{\text{hydrazone}}/t_{\text{N-Me}}$ (where hydrazone = Ib, R = *o*-MeO, *o*-Me, *o*-Cl, *o*-NO_2) also increases on passing from the less to the more polar solvents. This, together with the corresponding changes in intensity shown by the amino- and hydroxyl bands, strongly suggests that as the solvent is changed the amount of hydrazone tautomer increases in the order: cyclohexane < tetrachloroethylene < carbon tetrachloride < methylene chloride < chloroform < bromoform, and so confirms the findings of Burawoy and Thompson [3] from the

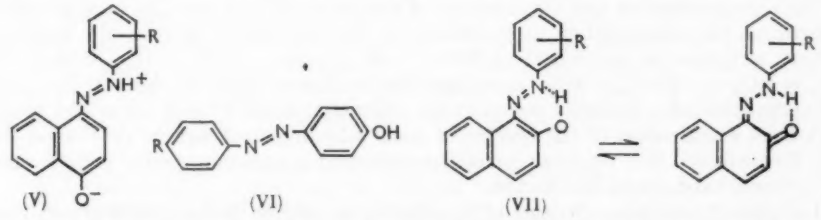
[23] Bellamy, "The Infra-red Spectra of Complex Molecules," Methuen, London, 1958.
[24] Flett, *J.*, 1948, 1441.
[25] See, *e.g.*, Bayliss, Cole, and Little, *Austral. J. Chem.*, 1955, **8**, 26; Archibald and Pullin, *Spectrochim. Acta*, 1958, **12**, 34; Thompson and Jewell, *ibid.*, 1959, **13**, 254.
[26] Bellamy, Hallam, and Williams, *Trans. Faraday Soc.*, 1958, **54**, 1120; Bellamy and Williams, *ibid.*, 1959, **55**, 14.

ultraviolet spectra. A similar order is found [27] for the effect of solvents on simple keto-enol tautomerism. Solvents can affect the position of equilibrium in two ways. Stabilisation of the hydrazone form is provided by the ability of the solvent to interact directly

TABLE 2. *Carbonyl bands in the spectra of* 4-*arylazo*-1-*naphthols.*

Substituent R in (I)		Solid	Solvent C_6H_{12}	C_2Cl_4	CCl_4	CH_2Cl_2	$CHCl_3$	$CHBr_3$
H		1625	—	—	—	1641	1634	1629
						370	320	190
						7·1	—	5·4
H		1632	1653	1649	1648	1636	1633	1629
(*N*-methyl			750	800	705	560	540	490
deriv., III)			10·9	12·0	12·3	13·4	14·0	11·7
o-MeO		1639	1650	1649	1648	1643	1641	1628
			745	710	700	580	445	390
	t		5·6	9·7	10·5	11·0	10·8	9·8
m-MeO		1630	—	—	—	1642	(1636)	1630
						410	380	—
	t					7·2	—	—
p-MeO		1625	—	—	—	1639	1630	1626
						120	104	—
	t					3·7	—	—
o-Me		1625	1648	1647	1647	1642	1638	1626
			120	180	170	365	290	280
	t		1·2	2·4	2·7	6·2	7·3	—
m-Me		1620	—	—	—	1641	1639	1628
						455	360	—
	t					6·8	7·9	—
p-Me		1625	—	—	—	1640	1633	1627
						310	210	—
	t					6·2	—	—
o-Cl		1625	1653	1652	1650	1644	1642	1636
			480	710	730	632	590	365
	t		6·7	7·1	7·3	8·9	10·0	9·1
m-Cl		1630	—	—	—	1643	1640	1635
						350	515	—
	t					—	8·8	—
p-Cl		1627	—	—	—	—	—	1633
o-NO_2		1640	—	1655	—	1651	1647	1643
				610		650	520	450
	t			6·4		10·4	10·4	10·9
m-NO_2		1627	—	—	—	1648	1643	1638
						340	455	—
	t					—	9·1	—
p-NO_2		1628	—	—	—	—	—	—

with the carbonyl group, probably through a weak hydrogen-bond; [26] additionally, an increase in dielectric constant stabilises the charge separation that accompanies the hydrazone tautomer, *i.e.*, stabilises the zwitterionic form (V). Both effects act to reduce



the carbonyl frequency and to displace the tautomeric equilibrium towards the hydrazone form. Direct solvent–solute interaction accounts most satisfactorily for the frequency shifts of simple carbonyl compounds,[26] and although the greater charge separation

[27] See, *e.g.*, Meyer, *Ber.*, 1912, **45**, 2843; Mecke and Funk, *Z. Elektrochem.*, 1956, **60**, 1124; Wilde Delvaux and Teyssié, *Spectrochim. Acta*, 1958, **12**, 289.

XUM

generated in this system may increase the contribution due to the change in dielectric constant, it seems possible that direct solvent–solute interaction is of paramount importance here also. This is supported by the results obtained from the isomeric 1-arylazo-2-naphthols (see below).

Superimposed on the solvent effect is that due to the substituents in the phenyl group. *meta*- and *para*-Substituents exert simple electron-donor and -acceptor forces on the hydrazono–azo-system. An sp^2 hybridised nitrogen atom is essentially more electronegative than one having sp^3 hybridisation;[28] additionally, while the lone pair in the azo-grouping lies close to the plane of the aromatic ring, in the hydrazone it is correctly orientated for interaction with the conjugated system. In consequence, the relatively electron-withdrawing azo-grouping (p-C_6H_5-N=N-, $\sigma_p = +0{\cdot}64$ [29]) is stabilised by electron-donating substituents and the position of equilibrium shifts accordingly. As a corollary it follows that the electron-donating properties of the hydrazono-group in the tautomer are

FIG. 1. *Correlation of the Hammett substitution constant* (σ) *with the frequency* (ν) *of the carbonyl band in the spectra of* 1-*arylazo*-4-*naphthols* (I) *in bromoform* ×, *chloroform* ○, *and methylene chloride* ●.

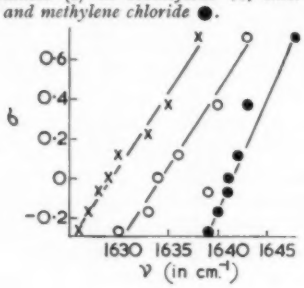
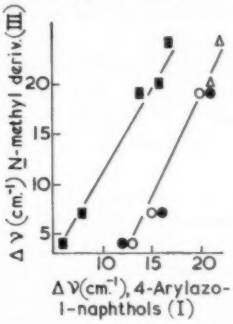


FIG. 2. *Correlation of frequency shifts* ($\nu_{CHBr_3} - \nu_{solv.}$) *of* 4-*arylazo*-1-*naphthols* (I, R = *o*-Me ●, *o*-OMe ○, *o*-Cl ■) *with those for naphthaquinone methylphenylhydrazone* (III). △ *denotes overlap of filled and open circles.*



increased by donor substituents and give lower carbonyl frequencies. Substituents in the *ortho*-position show rather different effects. The methoxy-, chloro-, and nitro-substituted derivatives all exist mainly in the hydrazone form. This is undoubtedly due to additional stabilisation of the hydrazone by internal hydrogen bonding; no such effect is shown by the *o*-tolyl derivative. It is noted that the solubility of the *ortho*-substituted derivatives is markedly higher than that of the *meta*- and *para*-isomers: this may be due to shielding of the polar nitrogen atoms by the *ortho*-substituent.

With the assumption that the intensity of the carbonyl band provides an approximate measure of the concentration of hydrazone in the tautomeric mixture, the hydrazone content increases in the order: p-MeO < o-Me ≈ p-Me < m-Me < H < m-MeO < m-Cl < m-NO_2 < o-MeO ≈ o-NO_2; a similar order is derived from the data on the amino- and hydroxyl bands; it closely resembles the order established [3,4] from ultraviolet spectra.

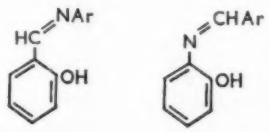
A brief examination of the spectra of some p-hydroxyazobenzenes (VI; R = MeO, NO_2, H) confirmed that these are correctly represented as azo-compounds: neither amino- nor carbonyl bands could be detected.

1-*Arylazo*-2-*naphthols*.—Neither in the solid nor in solution do the spectra of *o*-hydroxyazo-compounds show distinct bands in the hydroxyl stretching region.[15,16,30] In the spectra of the 1-arylazo-2-naphthols (VII) a series of weak, broad bands can be detected

[28] Walsh, *Trans. Faraday Soc.*, 1947, **43**, 60; Dewar and Schmeising, *Tetrahedron*, 1959, **5**, 166.
[29] Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, 1940, p. 188.
[30] Henricks, Wulf, Hilbert, and Liddel, *J. Amer. Chem. Soc.*, 1936, **58**, 1991.

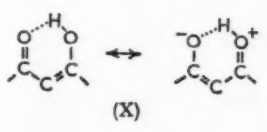
in the range 2400—3100 cm.$^{-1}$ and may be ascribed to a chelate hydrogen-bonded system. A similar effect is found in hydroxy-naphtha-[31] and -anthra-quinones[24] and in some Schiff's bases (VIII)[30] [but not in the isomeric compounds[32] (IX)]. These bands are of little use for diagnostic purposes.

A band appears in the spectra of the azo-compounds derived from β-naphthol near 1620 cm.$^{-1}$ (Table 3). This value can be compared with the frequency of the carbonyl bands found in the spectra of 1-hydroxy- and 1-amino-anthraquinones and anthrones[24] (1614—1633 cm.$^{-1}$) and of the corresponding naphthaquinones[31] (1623 cm.$^{-1}$) and there can be little doubt that it is correctly assigned to a carbonyl stretching frequency. The reduction of this frequency below that found in the derivatives of α-naphthol must be ascribed to strong internal hydrogen bonding:[33] confirmation of this is provided by the small shifts which accompany changes in solvent and indicate that the environment of the carbonyl group remains largely unaltered. The small changes that do occur may be indicative of the contribution made by dielectric changes to the larger shifts found in the 1,4-derivatives.

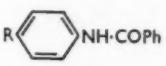


(VIII)

(IX)



(X)



(XI)

The intensity of the carbonyl band in the spectra of 1-arylazo-2-naphthols (Table 3) is considerably less than that of the 1,4-derivatives. As no adequate model compound is available for comparison, it is not immediately apparent whether the reduction in intensity is to be ascribed to a lower hydrazone concentration. The intensity of carbonyl bands has been correlated[34] with the availability of a charge-separated electronic configuration. In agreement with this, enolisable β-diketones[35] (X) and their amino-analogues[36] show intense carbonyl bands. A similar effect operates with both the 1,4- and the 1,2-azo-naphthols and will be differentiated only by the presence of internal hydrogen-bonding in the latter. This might be expected to increase the intrinsic intensity of the band, but comparison of the carbonyl bands in the spectra of *o*-hydroxy- and *o*-amino-benzaldehydes and -benzoates[37] with those of the unsubstituted and *para*-substituted compounds[38] shows that the former are slightly weaker. This effect clearly requires further investigation. It is possible that in the hydrazone some coupling of the carbonyl and aromatic C=C stretching modes near 1600 cm.$^{-1}$ occurs, but if so this cannot account for the reduction in intensity of the carbonyl band, for the aromatic band is in general weaker in the spectrum of the 1,2-compounds than the corresponding band in the spectrum of the 1,4-isomer.

The ultraviolet spectra were originally thought to indicate that the 1-arylazo-2-naphthols were largely present as hydrazones.[2,39] This was based on comparisons with inadequate model compounds,[11] and further examination suggested that comparable amounts of hydrazone are formed from both the 1,4- and the 1,2-derivatives.[5-8] Conversely, the weight of infrared evidence suggests that part at least of the diminution

[31] Josien, Fuson, Lebas, and Gregory, *J. Chem. Phys.*, 1953, **21**, 331.
[32] Baker and Shulgin, *J. Amer. Chem. Soc.*, 1959, **81**, 1523.
[33] Cf. Hunsberger, *J. Amer. Chem. Soc.*, 1950, **72**, 5626.
[34] Richards and Burton, *Trans. Faraday Soc.*, 1949, **45**, 874; Barrow, *J. Chem. Phys.*, 1953, **21**, 2008.
[35] Rasmussen, Tunnicliff, and Brattain, *J. Amer. Chem. Soc.*, 1949, **71**, 1068; Hergert and Kurth, *ibid.*, 1953, **75**, 1622.
[36] Cromwell, Miller, Johnson, Frank, and Wallace, *J. Amer. Chem. Soc.*, 1949, **71**, 3337.
[37] Krueger and Thompson, *Proc. Roy. Soc.*, 1959, *A*, **250**, 22.
[38] Thompson, Needham, and Jameson, *Spectrochim. Acta*, 1957, **9**, 208.
[39] Burawoy and Markowitsch, *Annalen*, 1933, **503**, 180.

XUM

in carbonyl intensity must be ascribed to a decrease in hydrazone concentration, and it may well be that the ultraviolet evidence overestimates the amount of hydrazone present.

TABLE 3. *Carbonyl bands in the spectra of* 1-*arylazo-2-naphthols.*

Substituent R in (VII)		Solid	Solvent C_6H_{12}	C_2Cl_4	CCl_4	CH_2Cl_2	$CHCl_3$
H		1622	1624	1623	1622	1622	1621
			190	195	200	215	230
	t		2·7	2·7	2·8	3·0	3·1
o-MeO		1615	1625	1624	1622	1622	1622
			265	280	285	295	370
	t		3·4	3·7	3·8	4·0	4·1
m-MeO		1622	1625	1623	1623	1621	1621
			195	195	210	225	250
	t		—	—	—	—	—
p-MeO		1612	1624	1624	1623	1622	1622
			185	185	190	205	210
	t		—	—	—	—	—
o-Me		1618	1624	1622	1621	1621	1621
			150	190	190	205	260
	t		1·9	2·5	2·6	2·7	2·9
m-Me		1620	1624	1623	1623	1622	1622
			190	195	195	220	260
	t		—	2·7	2·7	2·9	3·0
p-Me		1617	1624	1623	1622	1621	1620
			170	185	190	200	220
	t		2·2	2·6	—	2·8	2·9
o-Cl		1617	1623	1623	1622	1622	1621
			225	220	245	275	275
	t		3·2	3·3	3·3	3·7	3·9
m-Cl		1620	1625	1623	1623	1621	1622
			215	215	220	275	280
	t		3·0	3·0	3·1	3·4	3·5
p-Cl		1620	1625	1623	1623	1622	1622
			210	205	210	230	235
			2·8	2·8	2·9	3·2	3·3
o-NO_2		1622	—	1628	—	1624	1622
				285		290	285
	t			—		—	—
m-NO_2		1615	—	1625	—	1624	1621
				285		305	305
				3·7		—	3·9
p-NO_2		1625	—	—	—	1624	1624
						275	250
	t					—	—

It may be noted that in the 1-arylazo-2-naphthols internal bonding O–H · · · N will stabilise the azo-form by a mechanism not available to the 1,4-compounds. This bonding, and that in the complementary O · · · H–N system, involves orbitals in the plane of the aromatic rings and hence not directly linked to the conjugated system. It is to be expected that the more acidic phenolic form will be bonded the more strongly and in consequence be relatively stabilised.

The effect of both solvents and substituents on the intensity of the carbonyl band is analogous to that found for the 1,4-derivatives. The same solvent order is found, but the change in intensity is smaller and may be due largely to change in dielectric constant [40] since direct carbonyl–solvent interaction is inhibited. The effect of substituents also follows an order closely similar to that of the 1,4-derivatives. The greater solubility of the 1-arylazo-2-naphthols enables sufficient data to be collected to justify plots of intensity against Hammett substitution constants (σ). These plots (Fig. 3) are linear and demonstrate the quantitative dependence of the carbonyl intensity on the electron-withdrawing properties of the substituents. It is well known [37,38,41] that band intensities in

[40] Cf. Taft, Glick, Lewis, Fox, and Ehrenson, *J. Amer. Chem. Soc.*, 1960, **82**, 756.
[41] Thompson and Jameson, *Spectrochim. Acta*, 1958, **13**, 236.

many non-tautomeric compounds can be represented as linear functions of substitution constants. To examine whether a similar effect was responsible for the intensity changes here, a series of benzanilides (XI; R = H, MeO, Me, Cl, NO_2) was examined (the arylazonaphthols can be regarded as vinylogues of amides). The plot (Fig. 3) of the intensity of their carbonyl bands shows a small negative gradient (a similar result is provided by the data of Thompson and Jameson [41]) and confirms that the changes in intensity in the spectra of 1-arylazo-2-naphthols are due to changes in hydrazone concentration.

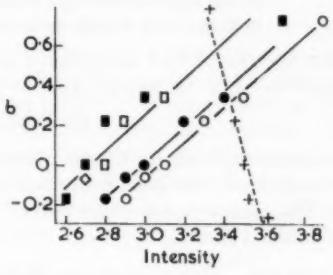


FIG. 3. *Correlation of the Hammett substitution constant (σ) with the intensity (t) of the carbonyl band in the spectra of* 1-*arylazo*-2-*naphthols* (VII) (*in chloroform* ○, *methylene chloride* ●, *carbon tetrachloride* □, *tetrachloroethylene* ■) *and* (t/3) *of the amides* (XI) (*in chloroform* +). ◇ *denotes overlap of filled and open squares.*

Structure of the Arylazonaphthols.—It was suggested [42] that the arylazonaphthols could be adequately represented by zwitterionic formulæ (*e.g.*, V). Such structures alone are incapable of interpreting the ultraviolet and infrared spectroscopic evidence and can be discounted. The presence of a tautomeric azo–hydrazone mixture in both 1-arylazo-2-naphthols and 4-arylazo-1-naphthols is clearly indicated, but the infrared spectra show that the structure of the hydrazones must contain some electronic displacement, *i.e.*, significant contribution from a zwitterionic canonical structure (*e.g.*, V). Equally to be discounted is the suggestion [1b,4,30] that no distinction can be drawn between the azo- and hydrazono-forms of the 1-arylazo-2-naphthols. The interaction between the mobile hydrogen atom and the adjacent oxygen and nitrogen atoms is best described in terms of a hydrogen bond whose potential-energy curve shows a double rather than a single minimum.

The author thanks Professor M. Stacey, F.R.S., for his interest and encouragement and Dr. J. K. Brown for helpful discussions.

DEPARTMENT OF CHEMISTRY, THE UNIVERSITY,
EDGBASTON, BIRMINGHAM, 15.

[*Received, July 7th*, 1960.]

[42] Kuhn, *Naturwiss.*, 1932, **20**, 622.

410. *Reactions of αα-Diphenyl-β-picrylhydrazyl with Phenols.*

By J. C. McGowan and T. Powell.

Reactions of αα-diphenyl-β-picrylhydrazyl with fourteen phenols have been studied. The results indicate that the phenolic groups are attacked in the step that determines the rates of the reactions. The increases in reactivity towards αα-diphenyl-β-picrylhydrazyl which result from extensions of the system of conjugated double bonds in phenols have been interpreted in terms of a simple molecular-orbital treatment.

The reactions [1-3] of αα-diphenyl-β-picrylhydrazyl with a number of phenols have been found to be of the second order so that

$$-\mathrm{d[Hydrazyl]}/\mathrm{d}t = k_2\mathrm{[Hydrazyl][Phenol]}$$

The rate constants for the reactions of αα-diphenyl-β-picrylhydrazyl with a further fourteen phenols have now been measured, and the reaction is discussed in the light of the results.

The measurements were carried out as described previously [1] and the results are given in Tables 1 and 2.

Table 1. *Reactions of phenols with αα-diphenyl-β-picrylhydrazyl in carbon tetrachloride (k is the bimolecular rate constant).*

Phenol	k (l. mole^{-1} min.$^{-1}$)	k (calc.)/k (obs.)
Phenols with a free ortho-*position*		
2-Phenylphenol	9·1 (18·7°)	—
2-Phenyl-4-t-butylphenol	36 (19·2°)	—
4-(α-Methylbenzyl)phenol	77 (19·8°)	1·0
4-(αα-Dimethylbenzyl)-phenol	89 (17·5°)	0·9
2,3-Bis-*p*-hydroxyphenyl-butane	104 (21·8°)	1·5 *
4-Phenylphenol	267 (20·3°)	—
4-Methyl-2-α-methylbenzyl-phenol	506 (19·8°)	1·2
2-Methyl-4-phenylphenol	1500 (18·6°)	—
4-Styrylphenol	6700 (19·8°)	—
4-Cyclohexyl-1-naphthol	~100,000 (20·0°)	—
2,6-Dimethylphenols		
2,3,5,6-Tetramethyl-phenol	816 (20·3°)	3·0
Pentamethylphenol	5690 (21·1°)	7·7
Phenols with bulky groups in both 2- and 6-positions		
2-Phenyl-6-t-butyl-phenol	36 (19·2°)	—
4,4′-Dihydroxy-3,3′,5,5′-tetra-t-butyl-diphenylmethane	56 (20·3°)	173 *

* Allowance has been made for the presence of two hydroxyl groups.

Table 2. *Rate constants k (l. mole^{-1} min.$^{-1}$) for bimolecular reactions of phenols with αα-diphenyl-β-picrylhydrazyl in benzene and in carbon tetrachloride.*

		In carbon tetrachloride		In benzene		In benzene at 30° (ref. 2)	
Phenol	2*a*	k	$RT\log_e k + 50a$	k	$RT\log_e k + 50a$	k	$RT\log_e k + 50a$
2-Chlorophenol	—	—	—	—	—	1·2	—
Phenol	1·512	4·3 (18·7°) [1]	38·7	1·3 (16·8°)	38·0	2·3	38·3
2-Methylphenol	—	47 (19·5°) [1]	—	—	—	19	—
4-Phenylphenol	1·437	267 (20·3°)	39·2	57 (17·6°)	38·3	—	—
2-Naphthol	1·455	377 (19·0°) [1]	39·8	132 (17·7°)	39·2	80	39·0
4-Styrylphenol	1·352	6700 (19·8°)	38·9	1600 (19·0°)	38·1	—	—
1-Naphthol	1·341	8000 (15·5°) [1]	38·7	2800 (19·0°)	38·1	3300	38·4

Discussion

McGowan, Powell, and Raw [1] found that the substitution of an alkyl group in the *para*-position of a phenol increased k, the rate constant for its reaction with αα-diphenyl-β-picrylhydrazyl, about 18 times. Each *meta*-alkyl group caused an approximately three-fold increase in k and when there was little steric hindrance an *ortho*-alkyl group increased

[1] McGowan, Powell, and Raw, *J.*, 1959, 3103.
[2] Godsay, Lohmann, and Russell, *Chem. and Ind.*, 1959, 1603.
[3] Venker and Herzmann, *Naturwiss.*, 1960, **47**, 133.

k about eight times. Calculated values of k at about 20° and with carbon tetrachloride as solvent were obtained by multiplication of 4·2 (k for phenol itself) by these factors. It will be seen from Table 1 that there is again fair agreement between the observed and calculated k values provided one *ortho*-position of the phenol is unsubstituted. For such phenols the ratios of calculated to observed values of k are near unity. When there are alkyl groups in both the 2- and the 6-position, the value of k is less than the calculated value, and the results reported here are in line with those reported previously.[1] It makes little difference whether or not there are hydrogen atoms attached to the α-carbon atom of an alkyl substituent. If such hydrogen atoms were directly involved in the reactions of phenols with αα-diphenyl-β-picrylhydrazyl, the substitution of a phenyl group on the α-carbon atom which carries the hydrogen would be expected to accelerate the reaction considerably. However, the α-methylbenzyl group has almost the same effect on the reaction as the methyl, the t-butyl, and the αα-dimethylbenzyl group. Further, the hydrogen atoms of the aromatic ring of the phenols do not appear to play an important rôle in the reaction because pentamethylphenol behaves normally. Table 2 shows that the reactions are about three times as fast in carbon tetrachloride as in benzene: examples where the reaction is faster in carbon tetrachloride than in toluene and in chloroform have been given.[1]

It might be expected that the αα-diphenyl-β-picrylhydrazyl radical would remove hydrogen from the phenol molecule and yield an aryloxy-radical ArO· as intermediate. It has, however, been suggested [1,4] that the intermediate may be an aryloxy-cation ArO^+ in which case the hydrazyl presumably combines with a hydride ion and yields a radical with a negative charge distributed over the nitro-groups. Whichever intermediate is formed, a relationship might be expected between the rate constants and the values, a, of the coefficients of the non-bonding orbitals on the carbon atoms of the methylene groups in the hydrocarbon radicals isoconjugate with the aryloxy-radicals. Longuet-Higgins [5] has given a simple method for the calculation of the non-bonding molecular orbital in alternant hydrocarbon radicals. The squares of these coefficients give the distribution of the odd electron in the radical. The distribution so calculated also gives, to a first approximation, the distribution of charge [6] in both the corresponding cation and anion. Also the structure and resonance energy of a heteroaromatic system are to a first approximation the same as those of the analogous hydrocarbon,[4,7] and Gray and Williams [8] have, for example, used the reactivities of the isoelectronic and more fully investigated radicals RCH_2· when they were considering the reactivities of the radicals RO·. Dewar and Sampson [9] have applied a simplified molecular-orbital method to the hydrolyses of arylmethyl chlorides and give

$$\boldsymbol{R}T \log_e k_2 = -2\beta a + D$$

Here β is the resonance integral between adjacent carbon atoms, which is normally between 20 and 30 kcal.,[9] and D is a constant. An equation [1] of this type should apply to the reactions of phenols with αα-diphenyl-β-picrylhydrazyl. For phenol, 4-phenylphenol, 1-naphthol, and 4-styrylphenol, $\boldsymbol{R}T \log_e k + 50a$ is approximately constant (see Table 2) for one solvent and one temperature. The value of $\boldsymbol{R}T \log_e k + 50a$ is however higher for 2-naphthol than for the other phenols. This suggests that a more reactive impurity may have been present in the 2-naphthol, although before use the 2-naphthol was

[4] McGowan, *J. Appl. Chem.*, 1960, **10**, 312.
[5] Longuet-Higgins, *J. Chem. Phys.*, 1950, **18**, 275.
[6] Longuet-Higgins, *Proc. Chem. Soc.*, 1957, 157; Dewar, "The Electronic Theory of Organic Chemistry," Oxford Univ. Press, 1949, p. 243.
[7] Coulson and Longuet-Higgins, *Proc. Roy. Soc., A*, 1947, **192**, 16; Dewar, *J. Amer. Chem. Soc.*, 1952, **74**, 3341.
[8] Gray and Williams, *Chem. Soc. Special Publ. No.* 9, 1957, p. 97.
[9] Dewar and Sampson, *J.*, 1956, 2789.

XUM

recrystallised and converted into its acetate which was recrystallised and hydrolysed to a sample which was again recrystallised.

IMPERIAL CHEMICAL INDUSTRIES LIMITED, PLASTICS DIVISION,
RESEARCH DEPARTMENT, BESSEMER ROAD,
WELWYN GARDEN CITY, HERTS.

[*Received, November 1st*, 1960.]

---

411. *Spectroscopic Studies of Quaternary Aldoximes and Ketoximes.*

By P. W. SADLER.

2,2′-Pyridil monoxime has the β-configuration and forms intramolecular N·OH···O·C bonds. Structures are tentatively assigned to the isomeric 2,2′-pyridil dioximes on the basis of their N–O stretching frequencies. The intensity of the C=N absorption is very variable in heterocyclic aldoximes and is particularly affected by quaternization which in general raises this frequency. Changes in frequency and intensity of this absorption are related to the reactivating properties of pyridine-2- and -4-aldehyde oxime derivatives for di-*O*-ethylphosphorylacetocholinesterase.

2,2-PYRIDIL MONOXIME (I) in the solid state has bonded O–H stretching frequencies at 3200 and 2800 cm.$^{-1}$ and a carbonyl stretching frequency at 1700 cm.$^{-1}$. These frequencies remain unchanged in dilute chloroform solution, indicating that bonding is intramolecular. Similar data are obtained for β-benzil monoxime in which the C=O mode occurs at the same frequency (1675 cm.$^{-1}$) in both solid and solution spectra. In the α-isomer this vibration shifts from 1645 cm.$^{-1}$ for the solid to 1670 cm.$^{-1}$ for solutions. Hence the monoxime of 2,2′-pyridil has the β-configuration. Earlier work has shown correlation between O–H stretching frequencies and the α- and β-forms of substituted benzaldoximes.[1] These have bands at 3250 and 3115 cm.$^{-1}$, respectively, in the solid state. Isomeric 2,2′-pyridil dioximes do not clearly differ in the 3 μ region (Table 1), but do in the N–O

TABLE 1. *Frequencies (cm.$^{-1}$) of isomeric 2,2′-pyridil and benzil oximes in potassium bromide discs.*

2,2′-Pyridil α-dioxime	3550	3250	3100	2900		1630	1590	1480	1435	1225	1095	1005	
2,2′-Pyridil β-dioxime		3200	3050	2900		1630	1590	1480	1440	1235	1095	1005—1095	970 945
2,2′-Pyridil β-monoxime		3200		2800	1700	1630	1580	1470	1435	1225	1090	1000—1094	965 935
Benzil α-dioxime	3400		3050					1490	1440	1220	1095	990	
Benzil β-dioxime	3450		3050			1600		1500	1440	1225	1075	985	960 940

stretching mode. Assignments [2] for this band have ranged from 800 to 1075 cm.$^{-1}$ (800—850, 900, 1020, and 975—1075). For benzil α-dioxime a single strong peak occurs in the N–O stretching region at 990 cm.$^{-1}$, whereas the β-dioxime shows more complex absorption with maxima at 940, 960, and 985 cm.$^{-1}$. As 2,2′-pyridil dioxime (m. p. 237°) has a single strong band at 1005 cm.$^{-1}$ and its isomer (m. p. 247°) has maxima at 970, 985, and 995—1005 cm.$^{-1}$, they are tentatively assigned the α- and the β-configuration respectively.

Two series of stereoisomers may be obtained for the quaternary pyridinium oxime derivatives.[3] Only those belonging to the more stable group are listed in Table 2. Attempts to assign configuration to the two series by chemical methods failed,[3] because quaternization need not occur with retention of configuration—quaternary ions may

[1] Palm and Werbin, *Canad. J. Chem.*, 1953, **31**, 1004.
[2] Haszeldine and Jandes, *J.*, 1954, 691; Tarte, *Bull. Soc. chim. belges*, 1953, **62**, 401; Giguère and Liu, *Canad. J. Chem.*, 1952, **30**, 948; Goubeau and Fromme, *Z. anorg. Chem.*, 1949, **258**, 18; O'Sullivan and Sadler, *J. Org. Chem.*, 1957, **22**, 283; Hadži, *J.*, 1956, 2725.
[3] Ginsberg and Wilson, *J. Amer. Chem. Soc.*, 1957, **79**, 481.

catalyse the isomerisation of oximes.[4] It is impossible to assign configurations to the oximes on the basis of their O–H stretching frequencies,[1] for these are complex owing to the formation of intermolecular bonds. Only tertiary aldehydes give oximes sufficiently soluble in non-polar solvents to provide records in the 3 μ region, and it has been suggested [5] that the presence of a non-bonded O–H absorption in pyridine-2-aldehyde oxime in carbon tetrachloride solution indicates the α-form (II) for the compound, as the β-form should show an intramolecular O–H···N bond. Further structural information is afforded by

TABLE 2. *Frequencies (cm.$^{-1}$) of oximes of tertiary and quaternary aldehydes in potassium bromide discs.*

No.												
1	HON·HC·$[CH_2]_2$·NMe_2Cl	3400	3200	3100		1640m			1480	1405	1295	1025	900
2	2-2′-Oxoethylpyridinium oxime chloride	3500		3050		1630m			1480	1420	1295	1060—1040	915
3	*NN*-Dimethyl-*p*-2′-oxoethylanilinium oxime chloride	3450	3150	3050	2850	1625w	1590		1490—1480	1410	1295	1030	985
4	*p*-Dimethylaminobenzaldoxime	3300	3150		2950	1610		1530			1300		960
5	*p*-Dimethylaminobenzaldoxime methochloride		3250	3050		1605vw			1480	1405	1280		970
6	Pyridine-2-aldehyde oxime		3250		2800	1620w	1595	1560	1510	1430	1320		980
7	Pyridine-2-aldehyde oxime methiodide			3050	2950	1620m		1570	1500	1420	1300		1000
8	Pyridine-2-aldehyde oxime isopropyloiodide		3200			1630m	1600	1570	1500	1450	1300		995
9	Pyridine-3-aldehyde oxime		3150		2800	1620w		1570	1510	1410	1305		990
10	Pyridine-4-aldehyde oxime		3150		2900	1640w	1600		1500	1420	1305		990
11	Pyridine-4-aldehyde oxime butyloiodide		3150		2750	1640m	1610	1590	1490	1425	1295		990
12	Pyridine-4-aldehyde oxime 3′-bromopropylobromide	3450		3050	2850	1640	1610		1480		1298—1290		1005
13	Pyridine-4-aldehyde oxime 5′-bromopentylobromide	3450		3050	2900	1650	1610		1480		1298—1290		1010
14	*NN′*-Trimethylene-bis-(4-hydroxyiminomethylpyridinium bromide)	3450	3150	3050	2900	1645	1610		1480		1295		1015
15	*NN′*-Tetramethylene-bis-(4-hydroxyiminomethylpyridinium bromide)	3500	3150	3050	2900	1640	1610		1485		1295		1000
16	4,4′-Dimethyl-2,2′-bipyridyl				2900		1590	1540		1450			
17	4,4′-Dimethyl-2,2′-bipyridyl dimethiodide				2950	1620		1575		1450			

Bands quoted are strong unless otherwise marked.

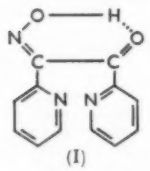
the O–H deformation mode. This has been examined for several groups of compounds [6] and identified between 1020 and 1420 cm.$^{-1}$. In particular, it has been demonstrated at 1300 and 1350 cm.$^{-1}$, respectively, in the Nujol spectra of the α- and the β-forms of substituted benzaldoximes.[7] The strong band at 1300 cm.$^{-1}$ for *p*-dimethylaminobenzaldoxime is lowered to 1280 cm.$^{-1}$ on quaternization. A similar shift (1320 to 1300 cm.$^{-1}$)

[4] Sidgwick, "The Organic Chemistry of Nitrogen," Clarendon Press, Oxford, 1942, p. 192.
[5] Hanania and Irvine, *Nature*, 1959, **183**, 40.
[6] Barchewitz, *Compt. rend.*, 1953, **237**, 237; Hadži and Sheppard, *Proc. Roy. Soc.*, 1953, *A*, **216**, 247; Quinan and Wiberley, *J. Chem. Phys.*, 1953, **21**, 1896.
[7] Palm and Werbin, *Canad. J. Chem.*, 1954, **32**, 858.

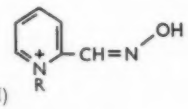
XUM

occurs in the spectra of the tertiary and the quaternary form of pyridine-2-aldehyde oxime, and a slightly smaller one for the 4-isomer. All the quaternary derivatives of these two oximes examined show this strong absorption near 1300 cm.$^{-1}$, which suggests the α-configuration.

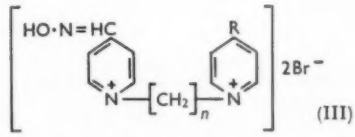
The C=N stretching frequency in spectra of aliphatic ketoximes [8] is fairly well defined at 1650—1675 cm.$^{-1}$, but aromatic ketoximes have been little studied. Acetophenone



(I)



(II)



(III)

oxime shows feeble absorption at 1630 cm.$^{-1}$ and the dioximes [9] of cyclohexane-1,2-dione and cycloheptane-1,2-dione have two weak bands at 1506 and 1524 cm.$^{-1}$. The C=N band was not found in the spectra of benzoin α-oxime, which casts doubt on the structure of this compound.[10] It is also absent from that of benzil α-dioxime, but is present as a weak-to-medium band at 1630 cm.$^{-1}$ for benzil β-dioxime and the oximes of 2,2′-pyridil (Table 1).

Aliphatic aldoximes have C=N bands between 1650 and 1670 cm.$^{-1}$; for aromatic compounds the range is 1614—1650 cm.$^{-1}$. Increased bond polarization which results from the formation of oxime dimers raises this frequency,[11] and quaternization of heterocyclic compounds produces a similar effect.[12] For most of the compounds listed in Table 2 both effects are possible, with the result that, in addition to frequency shifts, the relative intensities of the two C=N frequencies vary considerably. The C=N absorption occurs near 1595 cm.$^{-1}$ for pyridine derivatives and is raised to 1610 cm.$^{-1}$ on quaternization; in the case of 4,4′-dimethyl-2,2′-bipyridyl the increase is from 1590 to 1620 cm.$^{-1}$. Pyridine-2-aldehyde oxime shows two C=N frequencies, at 1595 and 1620 cm.$^{-1}$. The latter absorption, which results from the oxime group, is very weak, but is considerably increased in intensity on quaternization, and for the isopropyloiodide is also raised ten wave-numbers. Similar results are obtained for the tertiary and quaternary derivatives of pyridine-4-aldehyde oxime, the increase in intensity of the 1640 cm.$^{-1}$ band being even more marked. Quite different results are obtained with *p*-dimethylaminobenzaldoxime in which strong C=N absorption at 1610 cm.$^{-1}$ almost disappears on quaternization, while the N–O stretching frequency at 960 cm.$^{-1}$ is raised to 970 cm.$^{-1}$. The reactivating properties of the quaternary oximes for di-*O*-ethylphosphorylacetocholinesterase [13,14] are not directly related to the strong N–O stretching frequency which occurs in the region 960—1050 cm.$^{-1}$, but they are paralleled by the increase in frequency and intensity of the C=N absorption which ranges from 1620 to 1650 cm.$^{-1}$ for the active compounds.

In the isomeric pyridinealdehyde oxime methiodides the order of activity [14] is 2- > 4- > 3-, as indicated by their spectra (ultraviolet spectra of the methochlorides are similar [15]). If pyridine-2-aldehyde oxime derivatives have the α-configuration the hydroxy-imino-group is suitably projected to effect reactivation of the phosphorylated esteratic site. The length of the alkyl chain has little effect on either the ultraviolet

[8] Schecter and Conrad, *J. Amer. Chem. Soc.*, 1954, **76**, 2716; Cross and Rolfe, *Trans. Faraday Soc.*, 1951, **47**, 354; Brown, *J. Amer. Chem. Soc.*, 1955, **77**, 6341.
[9] Voter, Banks, Fassel, and Kehres, *Analyt. Chem.*, 1951, **23**, 1730.
[10] Duckaerts, *Bull. Soc. roy. Sci. Liége*, 1952, **83**, 614.
[11] Califano and Lüttke, *Z. phys. Chem.*, 1956, **6**, 83.
[12] Edwards and Singh, *Canad. J. Chem.*, 1954, **32**, 465; Witkop, *J. Amer. Chem. Soc.*, 1954, **76**, 5597.
[13] Hobbiger, O'Sullivan, and Sadler, *Nature*, 1958, **182**, 1498; Hobbiger and Sadler, *ibid.*, p. 1672; Hobbiger and Sadler, *Brit. J. Pharmacol.*, 1959, **14**, 192.
[14] Hobbiger, Pitman, and Sadler, *Biochem. J.*, 1960, **75**, 363.
[15] Mason, *J.*, 1960, 22.

spectra or the reactivities in this group (Table 3), but in the polymethylenebispyridinium dioximes (III; R = CH:N·OH) and the corresponding monoximes (III; R = H) bathochromic shifts occur in λ_1, and the hydrolytic power of the oximes is increased as the length of the alkyl chain diminishes.

TABLE 3. *Ultraviolet absorption spectra* (λ *in* mμ) *and reactivating properties of mono- and bis-quaternary formylpyridinium oximes.*

	λ_1	ε	Hydrol. of $Et_4P_2O_7$	Activity †
Pyridine-2-aldehyde oxime methiodide	330	18,700	1	1
" " ethiodide	335	18,490	1	0·54
" " propyloiodide	335	16,590	0·94	0·63
" " butyloiodide	335	16,500	1·1	0·87
Pyridine-4-aldehyde oxime methiodide	335	22,200	0·36	0·06
NN'-Trimethylene-1-(4-hydroxyiminomethylpyridium)-3-pyridinium dibromide	345	25,680	0·56	8·0
NN'-Tetramethylene homologue	337·5	24,530	0·53	6·7
NN'-Pentamethylene homologue	337·5	25,240	0·47	7·5
NN'-Ethylenebis-(4-hydroxyiminomethylpyridinium bromide)	352·5	44,460	1·5	17
NN'-Trimethylene homologue	347·5	44,000	1·1	22
NN'-Tetramethylene homologue	340	43,450	0·99	18
NN'-Pentamethylene homologue	340	43,400	0·91	16

† Potency as reactivator of diethylphosphorylacetocholinesterase.

Experimental.—Compounds in chloroform and potassium bromide discs were examined with a Perkin–Elmer 21 double-beam recording spectrophotometer. Ultraviolet absorption curves were determined for 0·1N-NaOH solutions, with matched quartz cells in a Hilger-Uvispek spectrophotometer. Preparative details have already been given.[13,14,16]

The author thanks the Department of Scientific and Industrial Research for a special grant which helped to defray the cost of this research.

MIDDLESEX HOSPITAL MEDICAL SCHOOL, LONDON, W.1. [*Received, November 14th*, 1960.]

[16] Pitman and Sadler, *J.*, 1961, 759.

---

412. *The Hydrogen Bonding of Imidazole in Carbon Tetrachloride Solution.*

By D. M. W. ANDERSON, J. L. DUNCAN, and F. J. C. ROSSOTTI.

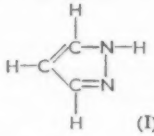
Analysis of the concentration-dependence of the infrared spectrum of imidazole in carbon tetrachloride solution at 18° ± 1° indicates that the fundamental N–H stretching band at 3485 ± 10 cm.$^{-1}$ is due to the free end-groups of linear oligomers. The number-average degree of polymerisation of the system increases from 1 to 2·6 in the concentration range 2×10^{-4} to 4×10^{-3}M, and the average number of monomeric units in each oligomer from 2 to 5. The hydrogen-bonding equilibria may be represented quantitatively by a dimerisation constant $\beta_{20} = 234 \pm 15$ l. mole^{-1} and subsequent, successive stepwise association constants K_q ($q \geqslant 3$) = 760 ± 20 l. mole^{-1}.

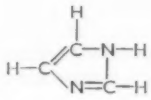
THE self-association of pyrazole (I) in carbon tetrachloride solution results in the formation of cyclic, hydrogen-bonded dimers and trimers.[1] Analogous cyclisations for imidazole (II) are impossible on steric grounds. Indeed, a consideration of bond angles suggests that any cyclic oligomer smaller than the decamer will have strained hydrogen bonds. The present study was undertaken to investigate the nature of the oligomers of imidazole which exist in carbon tetrachloride solution.

[1] Anderson, Duncan, and Rossotti, *J.*, 1961, 140.

XUM

A preliminary infrared spectroscopic examination of dilute solutions showed a fundamental N–H stretching mode at 3485 ± 10 cm.$^{-1}$ with a half-band width of 20 cm.$^{-1}$.


(I)

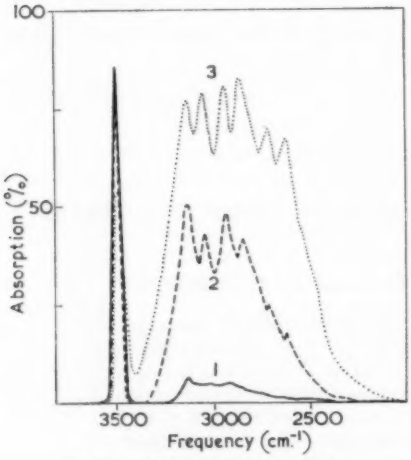

(II)

The intensity of this band decreased with increasing total concentration B of imidazole. Concurrently, a broad, hydrogen-bonded N–H band of increasing intensity appeared in the region 3400—2000 cm.$^{-1}$ (see Fig. 1). This broad band contained six major peaks (3125s, 3040s, 2925s, 2850s, 2705ms, and 2620 ms cm.$^{-1}$). The weak C–H band at 3120 cm.$^{-1}$ was completely masked. A quantitative study was accordingly made of the concentration dependence of the 3485 cm.$^{-1}$ band.

Experimental

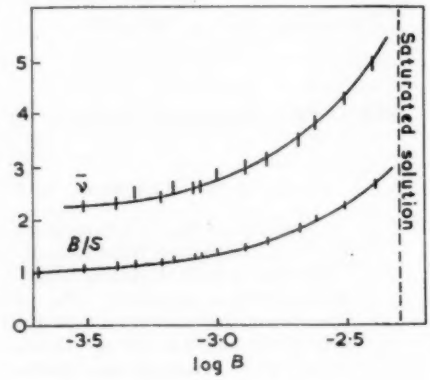
Materials.—Imidazole was recrystallised twice from carbon tetrachloride; it had m. p. 89·5° (lit., 90°). No O–H absorption spectrum was detectable in reagent-grade carbon tetrachloride, which was therefore used without further purification.

Fig. 1. *Infrared absorption spectra in the region 3800—2000 cm.$^{-1}$ for carbon tetrachloride solutions of imidazole at various total concentrations B at 18°.*



(1) $B = 10^{-4}$M. (2) $B = 10^{-3}$M. (3) $B = 5 \times 10^{-3}$M.

Fig. 2. *The number-average degree of polymerisation of the system B/S, and the average number of monomers per oligomer, $\bar{\nu}$, as a function of* log B. *The curve passing through the experimental points B/S,* log B *is calculated by substituting values of the stability constants obtained from eqns.* (15) *and* (16) *into eqns.* (3) *and* (5).



Infrared Measurements.—A Hilger H800 double-beam spectrophotometer fitted with a quartz prism was used. Operating conditions, calibration, and the precision of the frequency and intensity measurements were the same as reported previously.[1] A pair of carefully matched 4·00 cm. Unicam quartz cells was used for measurements in the concentration range $10^{-4} \leqslant B \leqslant 10^{-3}$M. A matched pair of cells of variable path-length, set at 5·000 ± 0·005 mm., and fitted with rock-salt windows, was necessary for more concentrated solutions.

Imidazole solutions of concentration $B > 4 \times 10^{-4}$M were prepared by semi-micro-weighing. More dilute solutions were prepared by dilution of a $1{\cdot}022 \times 10^{-3}$M-stock solution. Solutions were kept at 18° ± 1° throughout the measurement.

Procedure.—It was impossible to confirm that the intensity of the fundamental N–H stretching band of the free monomer conformed to Beer's law, as the most dilute solutions ($B \sim 10^{-4}$M) that could be studied were still slightly (~5%) hydrogen-bonded. The optics of the system were checked by confirming that the intensity of the 3485 cm.$^{-1}$ band adhered to Lambert's law. Solutions with $10^4B = 8{\cdot}176$, 8·743, and 10·22M were used in conjunction with the 4·00 and 0·500 cm. cells. The results conformed to Lambert's law within ±1%.

The concentration dependence of the intensity of the 3485 cm.$^{-1}$ band was then investigated. Details of the fifteen solutions used ($10^{-4} \leqslant B \leqslant 4 \times 10^{-3}$M) are listed in Table 1.

TABLE 1. *Infrared absorbancies at* 3485 *cm.*$^{-1}$ *of associated imidazole in carbon tetrachloride at* 18° ± 1° *and concentration variables derived therefrom.*

10^4B	$\log I_0/I$	10^4S	$\log b$	10^4B	$\log I_0/I$	10^4S	$\log b$	10^4B	$\log I_0/I$	10^4S	$\log b$
2·044	0·174	1·941	−3·718	6·800	0·495	5·523	−3·325	15·59	0·111 *	9·937	−3·138
3·066	0·252	2·810	−3·584	8·176	0·578	6·455	−3·271	20·62	0·130 *	11·57	−3·102
4·088	0·325	3·628	−3·483	8·743	0·607	6·777	−3·255	24·10	0·139 *	12·37	−3·086
4·857	0·374	4·170	−3·430	10·22	0·670	7·473	−3·223	31·19	0·157 *	14·00	−3·060
6·132	0·462	5·158	−3·350	12·78	0·098 *	8·750	−3·174	40·22	0·173 *	15·41	−3·043

* 5·000 mm. cells: other results refer to 4·00 cm. cells.

INTERPRETATION OF THE DATA

Calculation of Concentration Variables.—The value of the apparent molar extinction coefficient ε_1 of the monomer at 3485 cm.$^{-1}$ was obtained graphically as $\lim_{B\to 0} (\log I_0/I)/Bl$, where I_0 and I are the intensities of the incident and transmitted radiation, and l is the cell length. Only a short extrapolation was necessary to obtain the precise value $\varepsilon_1 = 224 \pm 2$.

The free N–H band in associated solutions might be due to free monomer only or to the free end-groups of linear oligomers. In the pyrazole system,[1] it was possible to distinguish between these possibilities by an argument based on the law of mass action. This rigorous approach cannot be applied to the imidazole system owing to the more extensive hydrogen bonding. However, a qualitative argument will show that the absorption is due to the end-groups of the oligomers. As compared with the pyrazole system, where the free N–H absorption is due to free monomer only,[1] the intensity of the broad, bonded N–H band of imidazole increased, as B increased, far more markedly than the intensity of the free N–H band decreased (compare Fig. 1 with Fig. 1 in ref. 1). Moreover, no bands or shoulders were detectable between the 3485 cm.$^{-1}$ band and the first bonded N–H band at 3125 cm.$^{-1}$, even for saturated solutions ($B \sim 5 \times 10^{-3}$M).

Accordingly, at 3485 cm.$^{-1}$, we may write

$$\log I_0/I = l\sum_1^Q \varepsilon_q B_q, \qquad (1)$$

where ε_q is the apparent molar extinction coefficient of the qth oligomer B_q (concentration B_q), and Q is the maximum value of q in the system. On the further reasonable assumption that all values of the extinction coefficients are approximately equal, we may transform eqn. (1) into

$$(1/\varepsilon_1 l) \log I_0/I = \sum_1^Q B_q = S \qquad (2)$$

and use eqn. (2) to calculate the end-group concentrations, S. These are given in Table 1. The total concentration B of imidazole is related to the free monomer concentration b by the equation

$$B = \sum_1^Q qB_q = \sum_1^Q q\beta_{q0}b^q \qquad (3)$$

where the self-association constants are defined by

$$\beta_{q0} = B_q b^{-q} \qquad (4)$$

XUM

Similarly,

$$S = \sum_{1}^{Q} \beta_{q0} b^q \tag{5}$$

B, S, and b are simply interrelated by Jannik Bjerrum's integral [2]

$$\log b/b_1 = (1/2{\cdot}303) \int_{S_1}^{S} (1/B)\mathrm{d}S \tag{6}$$

Hence, values of b may be calculated from the experimental data (B^{-1}, S) without any assumptions about the equilibria, provided that a value S_1, of S, corresponding to a known value b_1 of the monomer concentration can be selected. A point (S_1, b_1) was found by the following method suggested by Rossotti and Rossotti.[3] In sufficiently dilute solutions, where the dimer is the sole oligomer, eqns. (3), (4), and (5) may be combined to

$$\log (B - S) = \log \beta_{20} + 2 \log (2S - B) \tag{7}$$

The plot of log $(B - S)$ against log $(2S - B)$ tended to a straight line of slope 2 as $S \longrightarrow B$. A point (B_1, S_1) was found by solution of eqn. (7), and the corresponding value of b_1 by substitution into the equation

$$b_1 = (2S_1 - B_1)$$

Values of b, obtained by graphical integration using eqn. (6), are also included in Table 1.

The Degree of Polymerisation of the System.—By combining eqns. (3) and (5), we obtain [4]

$$B/S = \sum_{1}^{Q} qB_q / \sum_{1}^{Q} B_q = \sum_{1}^{Q} M_q B_q / M_1 \sum_{1}^{Q} B_q = \overline{M}_n / M_1,$$

where M_1, M_q, and $\overline{M}_n$ are the monomeric molecular weight, the molecular weight of the qth oligomer, and the number-average molecular weight respectively. The ratio B/S is clearly the number-average degree of polymerisation of the system, and may be obtained directly from the infrared measurements. In the restricted concentration range available to experiment, its value increases from unity to 2·6 (see Fig. 2). A better indication [3,5] of the nature of the oligomers present in solution is obtained by subtracting the monomeric term and calculating $\bar{\nu}$, the average number of monomers per oligomer. Values of $\bar{\nu}$, calculated by using the equation

$$\bar{\nu} = (B - b)/(S - b) = \sum_{2}^{Q} qB_q / \sum_{2}^{Q} B_q,$$

increase from ~2 to ~5, and increase sharply as saturation is approached (see Fig. 2). Consequently, at least the first six oligomers of the series B_q coexist in carbon tetrachloride solution.

Calculation of the Stability Constants.—Successive extrapolations. An attempt was made to obtain independent values of the self-association constants by a method of successive extrapolations.[3,4] Rearrangement of eqn. (3) gives

$$F_t = Bb^{-t} - \sum_{1}^{t-1} q\beta_{q0} b^{q-t} = t\beta_{t0} + (t+1)\beta_{t+1,0} b + \sum_{t+2}^{Q} q\beta_{q0} b^{q-t} \tag{8}$$

where t is an integer such that $2 \leqslant t \leqslant Q$. Values of $t\beta_{t0}$ and $(t + 1)\beta_{t+1,0}$ may be obtained as the intercept and limiting slope of the plots $F_t(b)$. Equation (5) may be treated similarly to give values of β_{t0} and $\beta_{t+1,0}$. The best set of parameters β_{q0} was found by alternate extrapolations of the functions $B(b)$ and $S(b)$. As is usually the case,[3-5] the precision of the experimental

[2] J. Bjerrum, *Kem. Maanedsblad*, **1943**, **24**, 21.
[3] Rossotti and Rossotti, *J. Phys. Chem.*, in the press.
[4] Rossotti and Rossotti, "The Determination of Stability Constants," McGraw-Hill, New York, **1961**.
[5] Rossotti and Rossotti, *J. Phys. Chem.*, in the press.

XUM

data was only sufficient to allow the first three self-association constants to be determined. Their values are given in Table 2.

Curve fitting. When the precision of experimental data does not permit the determination of $(Q - 1)$ independent stability constants, a quantitative description of the data is often possible in terms of one, two, or three independent parameters. These parameters may

FIG. 3. *The experimental data* log T (log b) *and* log θ (log b) *superimposed in the position of best fit on normalised curves calculated by using eqns.* (17) *and* (18).

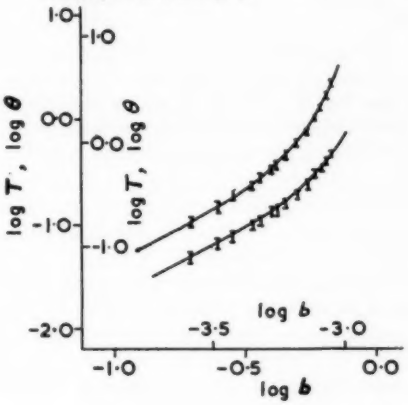
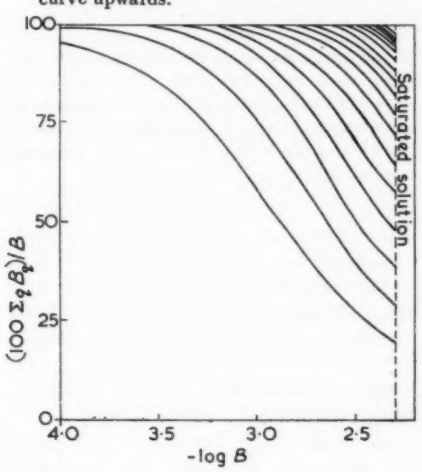


FIG. 4. *The percentage distributions* $(100\sum qB_q)/B$ *of the imidazole species* B_q *in carbon tetrachloride at* 18° *plotted as a function of* log B. The curves are for B_1, B_2, B_3, etc., from lowest curve upwards.



conveniently be determined by comparing suitable plots of the experimental data with normalised curves.[4,5]

Two auxiliary concentration variables are defined by

$$T = (B - b)b^{-1} \tag{9}$$

and

$$\theta = (S - b)b^{-1} \tag{10}$$

and the experimental data plotted in the form log T (log b) and log θ (log b) with common co-ordinate axes. These functions were compared with various pairs of normalised curves log $\boldsymbol{T}$ (log $\boldsymbol{b}$) and log $\boldsymbol{\theta}$ (log $\boldsymbol{b}$), calculated by Rossotti and Rossotti[4,5] for a number of models. The experimental curves were found to be of the same shape as a pair of normalised curves calculated on the assumptions described in ref. 5 as " Hypothesis I " (see Fig. 3). Hence, this hypothesis provides a valid description of the imidazole system in carbon tetrachloride solution.

On the simple model of " Hypothesis I," the stepwise association constants for the reactions

$$\overset{\bullet}{B}_{q-1} + B \rightleftharpoons B_q \quad (q \geqslant 3)$$

are all assumed to be equal and to have a value K. Hence

$$\beta_{q0} = \beta_{20}K^{q-2} \tag{11}$$

and by combining eqns. (3), (5), and (11)

$$T = \sum_{2}^{Q} q\beta_{20}K^{q-2}b^{q-1} \tag{12}$$

and

$$\theta = \sum_{2}^{Q} \beta_{20}K^{q-2}b^{q-1} \tag{13}$$

XUM

The analogous normalised variables are defined by

$$\boldsymbol{T} = TK/\beta_{20} \tag{14}$$

$$\boldsymbol{\theta} = \theta K/\beta_{20} \tag{15}$$

and

$$\boldsymbol{b} = bK \tag{16}$$

Equations (12)—(16) may be combined to yield

$$\boldsymbol{T} = \boldsymbol{b}(2 - \boldsymbol{b})/(1 - \boldsymbol{b})^2 \tag{17}$$

and

$$\boldsymbol{\theta} = \boldsymbol{b}/(1 - \boldsymbol{b}) \tag{18}$$

for a system in which $\boldsymbol{b} < 1$ and Q is very large. The normalised curves are calculated by using eqns. (17) and (18). The values of the parameters β_{20} and K are found by solving eqns. (16) and (14) or (15) in the position of best fit (see Fig. 3). The limits of errors of these parameters are found from the permissible displacements of the experimental functions log T (log b) and log θ (log b) over the normalised curves parallel to the co-ordinate axes. In this way, we find

$$\log \beta_{20} = 2{\cdot}37 \pm 0{\cdot}03$$

and

$$\log K = 2{\cdot}88 \pm 0{\cdot}01$$

Lassettre's method.[6] The only other two-parameter model in the literature was suggested by Lassettre [6] in 1937. For a system $B(S)$, which conforms to the linear equation

$$(B - S)/S^2 = (C_B B/S) + C_S$$

(where the parameters C_B and C_S denote a functional dependence of B/S upon B and S respectively), it may be shown that

$$\beta_{q0} = \frac{\prod_{m=0}^{m=q-2} [qC_B + (q - m)C_S]}{q!} \tag{19}$$

Our data $B(S)$ may be represented by the linear equation

$$(B - S)/S^2 = (470B/S) - 170 \tag{20}$$

Stability constants have been calculated by substituting the parameters of eqn. (20) into eqn. (19).

Discussion

Values of the first few self-association constants of the linear oligomers of imidazole, calculated by the various methods, are collected together in Table 2. Actual values of the equilibrium constants presumably lie within the ranges delineated by the various methods, which have given results in substantial agreement.

The percentage distribution of imidazole between the various oligomers has been calculated as a function of the total imidazole concentration B by using the constants obtained by curve fitting and eqn. (3). These data are shown in Fig. 4. Subject to the assumptions of the model, values of β_{q0} may be considered to be significant provided that the corresponding values of qB_q/B are significantly greater than zero. Hence, we find that significant concentrations of all oligomers up to the dodecamer ($q = 12$) are present in saturated solutions. Possibly, this fact explains the low solubility of imidazole ($\sim 5 \times 10^{-3}$M) compared with that pyrazole (>M) in carbon tetrachloride at 18°.

Dimeric and trimeric pyrazole are less stable thermodynamically than the dimers and trimers of imidazole, in spite of the fact that the former are cyclic and the latter linear. In the imidazole system, the equilibrium constant for the association of monomer with monomer is smaller than the equilibrium constant for the association of monomer with

[6] Lassettre, *J. Amer. Chem. Soc.*, 1937, **59**, 1383.

any larger oligomer (*i.e.*, $\beta_{20} < K$). This is to be expected both on the grounds of Saroléa-Mathot's statistical treatment [7] concerning the entropy term and from electrostatic considerations [8] concerning the enthalpy term. According to the statistical treatment,[7]

TABLE 2. *Self-association constants for the imidazole system obtained by various methods.*

	Eqn. (7)	Eqn. (8)	Eqns. (15) & (16)	Eqns. (19) & (20)
$\log \beta_{20}$	2·45 ± 0·03	2·38 ± 0·02	2·37 ± 0·03	2·48 ± 0·04
$\log \beta_{30}$		5·23 ± 0·03	5·25 ± 0·04	5·20 ± 0·04
$\log \beta_{40}$		~8·00	8·13 ± 0·05	8·02 ± 0·05
$\log \beta_{50}$			11·01 ± 0·06	10·89 ± 0·05
$\log \beta_{60}$			13·89 ± 0·07	13·78 ± 0·05
$\log \beta_{q0}$			2·37 + (*q* − 2)2·88	Cf. eqn. (19)

the ratio K/β_{20} equals the number of equivalent orientations of the monomer in the solvent. The present value of ~3 is approximately equal to values reported elsewhere [5] for 2-n-butylbenzimidazole and some amides in benzene solution.

Within the experimental precision, the free N–H groups in both the pyrazole and imidazole systems have been found to absorb at an identical frequency (3485 ± 10 cm.$^{-1}$) and with identical apparent molar extinction coefficients $\varepsilon_1 = 222 \pm 4$. These facts lend some support to our assumption in eqn. (2) that the various oligomers of imidazole have equal extinction coefficients. It is noteworthy that the bonded N–H regions from 3400 to 2000 cm.$^{-1}$, each with six peaks, are remarkably similar for both the pyrazole and the imidazole system. However, the self-association of imidazole in carbon tetrachloride is far more extensive than that of pyrazole. The latter only forms cyclic dimers and trimers, whereas imidazole (like 2-n-butylbenzimidazole in benzene [5,9]) forms a large number of linear oligomers. A comparison of Figs. 1 and 4 suggests that the peak at 3125 cm.$^{-1}$ may tentatively be assigned to the bonded N–H absorption of the dimer, and the remainder of the band to the bonded N–H absorptions of all larger oligomers, B_q ($q > 2$), which will be expected to have similar spectra.

We thank the Carnegie Trust for a Research Scholarship to J. L. D.

DEPARTMENT OF CHEMISTRY, UNIVERSITY OF EDINBURGH. [*Received, November 18th*, 1960.]

[7] Saroléa-Mathot, *Trans. Faraday Soc.*, 1953, **49**, 8.
[8] Coggeshall, *J. Chem. Phys.*, 1950, **18**, 978.
[9] White and Kilpatrick, *J. Phys. Chem.*, 1955, **59**, 1044.

---

413. *The Kinetics of Complex-formation of 1,3,5-Trinitrobenzene with Diethylamine and Other Amines in Solution at Low Temperatures.*

By C. R. ALLEN, A. J. BROOK, and E. F. CALDIN.

The kinetics of the reaction between diethylamine and 1,3,5-trinitrobenzene, which is thought to produce a charge-transfer complex, have been studied at low temperatures by the stopped-flow method. They indicate that the reaction is reversible, of first order in trinitrobenzene, and of second order in diethylamine. The rates, equilibrium constants, ΔH, ΔS°, and the Arrhenius parameters have been determined. The results are interpreted in terms of solvation changes and a preliminary equilibrium. The reactions of trinitrobenzene and trinitrotoluene with various aromatic amines, on the other hand, are too fast for measurement by the present technique.

IN recent work on low-temperature kinetics in this laboratory, the rates have been measured of several reactions which appear to be complex-formations between the ethoxide ion and

various nitro-compounds.[1,2] It is of interest to extend the investigations to complex formation between neutral molecules. A good deal is known about the thermodynamics of these complexes, and the theory of charge-transfer complexes has been developed by Mulliken and others.[3] The complexes of 1,3,5-trinitrobenzene (T.N.B) with aromatic amines and hydrocarbons have been studied by several authors;[4,5,6] they are highly coloured products, formed instantaneously at room temperature, and are probably charge-transfer complexes. The complexes of trinitrobenzene with aliphatic amines, which are also highly coloured, have been studied by Miller and Wynne-Jones[6] and by Foster.[7] Both investigations led to the suggestion that the initial product is a charge-transfer complex. We have studied the rates of formation of these coloured products, with the help of a low-temperature photometric stopped-flow apparatus recently described.[8] The reactions with aromatic amines are too fast for measurement by this technique, but the reaction with diethylamine is measurable. It appears to be a third-order reversible reaction, and we have measured rates and equilibria in selected solvents over ranges of temperature, in order to determine ΔH, ΔS^0, and the Arrhenius parameters E and A.

Experimental

The Low-temperature Stopped-flow Apparatus.—The mode of operation was described in our previous paper,[8] except for the following. Improvements to the non-return valves resulted in much more uniform relative rates of delivery of the two reactant solutions from their reservoirs, so that it was possible to simplify the determination of the relative rates as follows. Before each set of 5 or 6 identical kinetic runs, 6 blank runs were carried out at the same temperature with the pure solvent in one reservoir and in the other a solution of acetic acid in the same solvent; the mixed product from these blank runs (after the effluent of the first of them had been rejected) was analysed by titration, and the mean relative rates of delivery thus obtained. After the set of kinetic runs, this procedure was repeated. The two values for the relative rates nearly always agreed within about 1%, and could safely be assumed to apply to the kinetic runs. The rate constants derived from a set of 5 or 6 identical kinetic runs usually gave a standard deviation from the mean of 1—2% (cf. Tables 2a and 2b below).

Choice of Solvent.—Aromatic amines. The reactions with aromatic amines had to be studied at the lowest temperature possible; the limit was set by the increase of viscosity and decrease of solubility with decrease of temperature. Solubilities for α-naphthylamine and trinitrobenzene in solvents of suitably low viscosity and freezing point were systematically investigated, by stirring an excess of the solute with the solvent, drawing off samples of the saturated solution through a sintered-glass filter into the cell of a Unicam spectrophotometer, and determining the concentration of the solution by measurement of the optical density at three wavelengths. The best solvent was found to be acetone–diethyl ether, in a molar ratio 1 : 3; this solidifies below −135°. The solubility at −123° of trinitrobenzene in this solvent is 0·024 and that of α-naphthylamine is 1·2 mole $l.^{-1}$; the complex is the least soluble component of the mixture, but an adequate optical density can be obtained without precipitation at −135°. Other solvent systems investigated were toluene–acetone and toluene–ether, in various proportions, but the solubilities of trinitrobenzene were too low. As regards viscosity, which must not be too high if proper mixing is to be obtained, theory indicates that ether is satisfactory at least down to −127° and acetone at least down to −110°, and experiments have suggested that these calculated limits are too high.[8]

Trinitrobenzene and diethylamine. For this reaction the rate is such that the temperature need not be lower than −100°, and the important factors are the solubility of the amine and the

[1] Caldin and Long, *Proc. Roy. Soc.*, 1955, *A*, **226**, 263.
[2] Ainscough and Caldin, *J.*, 1956, 2528, 2540, 2546.
[3] Mulliken, (*a*) *J. Amer. Chem. Soc.*, 1952, **74**, 811; (*b*) *J. Phys. Chem.*, 1952, **56**, 801; (*c*) Reid and Mulliken, *J. Amer. Chem. Soc.*, 1954, **76**, 3869; (*d*) Mulliken, *Rec. Trav. chim.*, 1956, **75**, 845; (*e*) Orgel and Mulliken, *J. Amer. Chem. Soc.*, 1957, **79**, 4839; (*f*) Plyler and Mulliken, *ibid.*, 1959, **81**, 823.
[4] Bier, *Rec. Trav. chim.*, 1956, **75**, 866.
[5] Foster and Hammick, *J.*, 1954, 2685.
[6] Miller and Wynne-Jones, *J.*, 1959, 2375.
[7] Foster, *J.*, 1959, 3508.
[8] Allen, Brook, and Caldin, *Trans. Faraday Soc.*, 1960, **56**, 788.

XUM

equilibrium constant, which limit the optical density obtainable. In all solvents the optical density increases with decrease of temperature, presumably because the equilibrium constant increases. Acetone, and acetone–ether (1 : 3), were found to be satisfactory solvents. It is difficult to prepare acetone free from water, and 0·1% of water corresponds to a molar concentration of about 0·05, which is comparable with the lower concentrations of diethylamine used. Some runs were therefore carried out in which a volume of water equal to that of the diethylamine was added to acetone solutions; the molar ratio of water to diethylamine was 5·8. We refer to the solvent in these runs as acetone–water. It was not possible to add water in this way to acetone–ether, since its solubility at low temperatures is inadequate.

Spectrophotometry.—For the complexes with aromatic amines, the extinction coefficients and equilibrium constants in chloroform solution have been determined by Bier.[4] Similar values in the acetone–ether (1 : 3) at 25° were obtained for the α-naphthylamine–trinitrobenzene complex, by measuring optical densities and using the treatment recommended by Benesi and Hildebrand; [9] the results were $\varepsilon = 1040$ l. mole^{-1} cm.$^{-1}$, $K = 3{\cdot}8$ l. mole$^{-1} = 41$ (mole fraction)$^{-1}$, $\lambda_{max.} = 464$ mμ. A combination of Chance OY 8 and OB 10 glass filters was used in investigating the rate of formation of this complex; for the other aromatic-amine complexes, a Chance OB 10 or an Ilford 806 filter was used. For the diethylamine–trinitrobenzene complex, no data were available since previous measurements [6,7] have been made at room temperature and are therefore not concerned with the reaction here being studied. The complex is orange-coloured and in the kinetic runs a Chance OB 10 glass filter was used; the half-length of the absorption band of the filter runs from 365 to 475 mμ.

Materials.—1,3,5-Trinitrobenzene was recrystallised 3 times from ethanol and had m. p. 121—122°. Aromatic amines were distilled, and stored, under reduced pressure. Diethylamine was distilled from sodium hydroxide, and the fraction boiling between 55·5° and 55·6° collected (lit., 55·5°). Diethyl ether was refluxed over sodium and distilled; it had b. p. 34·6° (lit., 34·6°). Acetone was dried with potassium carbonate and distilled, then having b. p. 55·5—56·0° (lit., 56·1°).

Results

Rates of Reaction of Trinitro-benzene and -toluene with Aromatic Amines.—These reactions were studied with the minimum concentrations required to give a sufficient optical density, at the lowest practicable temperature. The solvent was acetone–ether (1 : 3 molar). The amines were chosen for the relatively high values of the equilibrium constants of their complexes, and the convenient positions of their charge-transfer bands.[4,5] The reactions were all complete within a millisecond, so the first-order rate constants were all >700 sec.$^{-1}$. If the reactions are assumed to be second-order, the corresponding minimum values of the second-order rate constant k lie between 10^3 and 10^4 l. mole^{-1} sec.$^{-1}$ (Table 1). If A is assumed to be 10^{11} l. mole^{-1} sec.$^{-1}$, the corresponding maximum values of the Arrhenius energy of activation E are in the region of 5·5 kcal. mole^{-1}.

Table 1. *Rates of reaction of trinitro-benzene* (T.N.B.) *and -toluene* (T.N.T.) *with aromatic amines in acetone–ether* (1 : 3 molar).

Donor	Donor concn. (mole/l.)	Acceptor	Acceptor concn. (10^{-3} mole/l.)	Temp.	$10^{-3}k$ (l. mole^{-1} sec.$^{-1}$)
α-Naphthylamine	0·26	T.N.B.	0·81	−134°	>3
p-Toluidine	0·31	T.N.B.	2·39	−120	>2
Diphenylamine	0·29	T.N.B.	2·39	−120	>2
N-Methylaniline	0·11	T.N.T.	0·58	−120	>6
N-Ethylaniline	0·10	T.N.T.	0·58	−120	>6
NN-Diethylaniline	0·14	T.N.T.	0·58	−120	>5

Rate of Reaction of Trinitrobenzene with Diethylamine.—Runs were carried out in acetone–ether (1 : 3 molar), in acetone, and in acetone–water containing 5·8 moles of water per mole of diethylamine. In each run, the concentration of amine (b) was at least 100 times that of trinitrobenzene (d). The half-lives range from 0·05 to 1 sec. First-order plots prepared by Guggenheim's method [10] were always linear within experimental error; this implies that the

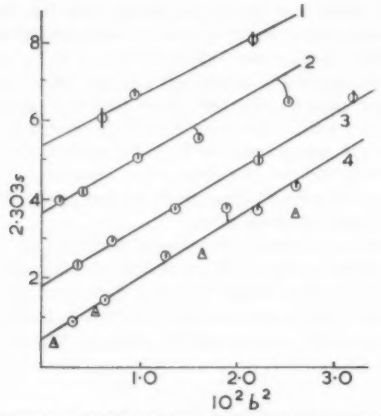
[9] Benesi and Hildebrand, *J. Amer. Chem. Soc.*, 1949, **71**, 2703.
[10] Guggenheim, *Phil. Mag.*, 1926, **2**, 538.

XUM

reaction is of the first order with respect to trinitrobenzene, and that Beer's law is obeyed. The slopes of these plots could be estimated to about ±2%. We denote the numerical value of the slope by s. At each concentration of amine, five or six runs were carried out, and the mean value of s was calculated, with the standard deviation. These values of s are given in the fifth columns of Tables 2*a* and 2*b*.

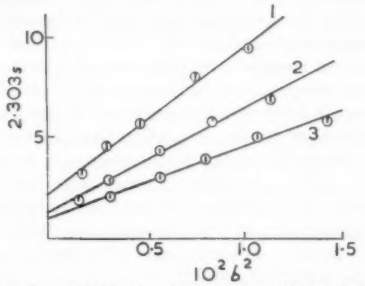
The values of s when plotted against b^2 give good straight lines, at least up to diethylamine concentrations (b) of about 0·15M; the intercept increases with temperature. The plots are

FIG. 1*a*. *Plot of s against b^2 for the reaction of diethylamine with trinitrobenzene in acetone–ether.*



Line 1, −58·9° (displaced 3 units downwards); 2, −66·7°; 3, −70·6°; 4, −84·8°; triangles, −85·6°. The lengths of the short lines represent standard deviations.

FIG. 1*b*. *Plot of s against b^2 for the reaction of diethylamine with trinitrobenzene in acetone–water.*



Line 1, −29·0°; 2, −39·3°; 3, −49·5°. The lengths of the short lines represent standard deviations.

shown in Figs. 1*a* and 1*b*. The linear s–b^2 relation is characteristic of a reversible reaction of the type $A + 2D \rightleftharpoons AD_2$, where A represents the acceptor trinitrobenzene and D the donor diethylamine. Such a reaction scheme predicts the following relation (see Discussion) when diethylamine is in large excess:

$$2{\cdot}303s = b^2k + k_b, \qquad (1)$$

where k_f and k_b are the rate constants for the overall forward and reverse reactions, and are given respectively by the slope and intercept of the plot of s against b^2. Values of k_f and k_b derived from least-squares treatment of the plots are given, along with standard deviations, in Tables 2*a* and 2*b*.

Heats and Entropies of Activation.—The Arrhenius plots of log k_f and log k_b against $1/T$ give values of the energies of activation and A factors for the forward and back reactions; these are designated by E_f and E_b, A_f and A_b. The best values from a least-squares treatment, along with standard deviations, are given in Table 3. Values of the entropies and enthalpies of activation ΔS^* and ΔH^*, calculated from the relations $A = e(\boldsymbol{k}T/\boldsymbol{h}) \exp(\Delta S^*/\boldsymbol{R})$ and $\Delta H^* = E + \boldsymbol{R}T$, are also included in Table 3.

Equilibrium Data on the Trinitrobenzene–Diethylamine Reaction.—Qualitative observations on the depth of colour of solutions show (i) that in all solvents the equilibrium shifts in favour of the complex as the temperature falls, so that the forward reaction must be exothermic, and (ii) that there is considerably more complex-formation in acetone or acetone–water than in ether, ethanol, propan-2-ol, toluene, or acetone–ether. Quantitative data are obtained from the kinetic runs; the overall equilibrium constant $K = (AD_2)/(A)(D)^2 = k_f/k_b$. Values of K derived from those of k_f and k_b are given in Tables 2*a* and 2*b*. The corresponding values of $\Delta H = E_f - E_b$ and of $\Delta S^\circ = \boldsymbol{R} \ln (A_f/A_b)$ are given in Table 3. The standard state to which

TABLE 2*a*. *Reaction of diethylamine with trinitrobenzene* (T.N.B.) *in acetone and ether* (1 : 3).

Concn. of diethylamine = b; concn. of T.N.B. = d.
Corrections for change of density with temperature have been applied.
Uncertainties are standard deviations.

Temp.	10^4d (mole/l.)	10^2b (mole/l.)	No. of runs	Mean $2{\cdot}303s$ (sec.$^{-1}$)	$10^{-2}k_f$ (l.^{2} mole^{-2} sec.$^{-1}$)	k_b (sec.$^{-1}$)	$10^{-2}K$ (l.^{2} mole^{-2})
−85·60°	1·49	16·2	5	3·91 ± 0·03	1·32 ± 0·09	$0{\cdot}5_8$ ± 0·15	2·3 ± 0·9
	1·49	12·9	5	2·93 ± 0·05			
	1·49	7·6	5	1·42 ± 0·01			
	1·49	3·8	6	0·62 ± 0·01			
−84·83	6·33	16·2	5	4·58 ± 0·08	1·56 ± 0·11	$0{\cdot}6_8$ ± 0·20	2·3 ± 1·0
	4·06	14·9	4	4·00 ± 0·03			
	6·33	13·8	5	4·00 ± 0·08			
	6·33	11·3	5	2·82 ± 0·08			
	6·33	8·2	5	1·64 ± 0·01			
	6·33	5·7	5	1·08 ± 0·01			
−70·56	3·33	17·9	5	6·87 ± 0·11	1·49 ± 0·04	1·97 ± 0·08	0·76 ± 0·07
	3·33	14·9	5	5·18 ± 0·16			
	3·33	11·7	5	3·96 ± 0·04			
	3·33	8·6	5	3·16 ± 0·03			
	3·33	6·1	5	2·53 ± 0·07			
−66·72	1·45	15·9	5	6·67 ± 0·08	1·46 ± 0·05 *	$3{\cdot}8_3$ ± 0·1	0·38 ± 0·03
	1·45	12·7	5	5·82 ± 0·06			
	1·45	9·9	5	5·29 ± 0·04			
	1·45	6·5	5	4·38 ± 0·07			
	1·45	4·4	5	4·17 ± 0·05			
−58·92	1·17	14·7	5	11·31 ± 0·20	1·28 ± 0·04	8·6 ± 0·1	0·15 ± 0·01
	1·17	9·8	5	9·94 ± 0·09			
	1·17	7·8	5	9·26 ± 0·25			

* Calculated from results at three lowest concentrations only.

TABLE 2*b*. *Reaction of diethylamine with trinitrobenzene in acetone–water*

(Notes are in Table 2*a*.)

Temp.	10^4d (mole/l.)	10^2b (mole/l.)	No. of runs	Mean $2{\cdot}303s$ (sec.$^{-1}$)	$10^{-2}k_f$ (l.^{2} mole^{-2} sec.$^{-1}$)	k_b (sec.$^{-1}$)	$10^{-2}K$ (l.^{2} mole^{-2})
−49·49°	1·08	12·0	5	5·88 ± 0·10	3·52 ± 0·13	0·99 ± 0·14	3·5 ± 1
	1·08	10·4	5	5·06 ± 0·08			
	1·08	9·1	5	3·92 ± 0·08			
	1·08	7·7	5	3·06 ± 0·04			
	1·08	5·7	5	2·06 ± 0·06			
−39·27	1·19	10·7	5	6·90 ± 0·14	5·13 ± 0·11	1·26 ± 0·09	4·1 ± 0·6
	1·19	9·2	5	5·91 ± 0·11			
	1·19	7·6	5	4·37 ± 0·09			
	1·19	5·7	5	2·93 ± 0·05			
	1·19	4·2	5	1·94 ± 0·06			
−28·98	1·38	10·2	5	9·53 ± 0·08	7·28 ± 0·36	2·21 ± 0·17	3·3 ± 0·7
	1·38	8·7	5	8·08 ± 0·27			
	1·38	7·0	5	5·70 ± 0·12			
	1·38	5·6	5	4·64 ± 0·13			
	1·38	4·2	5	3·27 ± 0·09			

TABLE 3. ΔH, ΔS^0, E, A, ΔH^*, *and* ΔS^* *for reaction of diethylamine with trinitrobenzene.*

All value are " best " values by least squares, with standard deviations. Standard entropies are at 1 mole l.$^{-1}$.

	Acetone–ether	Acetone–water
ΔH (kcal. mole^{-1})	−7·7 ± 0·8	−0·2 ± 1·5
ΔS° (cal. deg.$^{-1}$ mole^{-1} at 25°)	−30 ± 4	+10 ± 6
E_f (kcal. mole^{-1})	0 ± 0·2	3·8 ± 0·3
E_b (kcal. mole^{-1})	7·7 ± 0·6	4 ± 1
$\log_{10} A_f$ (A_f in l.^{2} mole^{-2} sec.$^{-1}$)	2·2 ± 0·2	6·3 ± 0·3
$\log_{10} A_b$ (A_b in sec.$^{-1}$)	8·8 ± 0·7	4 ± 1
ΔH^*_f (kcal. mole^{-1} at 25°)	0·6 ± 0·6	4·4 ± 0·3
ΔH^*_b (kcal. mole^{-1} at 25°)	8·3 ± 0·6	5·6 ± 1
ΔS_f^* (cal. deg.$^{-1}$ mole^{-1} at 25°)	−50 ± 1	$-31{\cdot}_8$ ± 1·5
ΔS_b^* (cal. deg.$^{-1}$ mole^{-1} at 25°)	−20 ± 3	−42 ± 4·5

XUM

ΔS^* refers is an ideal solution of concentration 1 mole $l.^{-1}$. Some rough estimates of the optical density at equilibrium give values for the extinction coefficient of the order of 10^3.

Discussion

The Nature of the Complex between 1,3,5-Trinitrobenzene and Diethylamine.—Recent work [6,7] has shown that trinitrobenzene and diethylamine can undergo a series of reactions. Foster [7] followed the development of optical density with time in chloroform solutions at room temperature; he observed an initial instantaneous reaction, followed by changes lasting several minutes. The composition of both the initial and the final product was 3 molecules of diethylamine to 1 of trinitrobenzene. It was suggested that the initial instantaneous product was a charge-transfer complex, and the final product a covalent compound. At the temperatures and concentrations used in the present work, the rates of the later reactions are negligible, and our results refer to the initial reaction. The molar ratio in our solvents appears to be 2 : 1, as the next section shows.

The Mechanism of the Reaction between Trinitrobenzene and Diethylamine.—Interpretation of the rate–concentration relation. The observed linear relation between the first-order constants of the individual runs and the squares of the diethylamine concentrations,

$$2{\cdot}303s = b^2k_f + k_b. \qquad (1)$$

may be explained on the assumption that the rate-determining process is a reversible reaction producing a complex of formula AD_2:

$$A + 2D \underset{k_b}{\overset{k_f}{\rightleftharpoons}} AD_2. \qquad (2)$$

It is, however, important to enquire whether the experimental results are compatible with alternative schemes. A possible scheme, leading to a complex AD, is:

$$A + D \underset{k_b}{\overset{k_f}{\rightleftharpoons}} AD. \qquad (3)$$

This would lead to the relation:

$$2{\cdot}303s = bk_f + k_b. \qquad (4)$$

Our results are not compatible with this relation, since plots of s against b are curved; the points at higher concentrations might be represented quite well by straight lines, but these lines would give negative intercepts which would be difficult to interpret. These results cannot be attributed to the unavoidable traces of water present in acetone, in quantities comparable to the lower concentrations of diethylamine, since they are observed also when water equivalent to the diethylamine is added. An alternative scheme, in which AD_2 is first formed as in equation 2 and then dissociates in a rapid equilibrium to AD + D, also leads to equation 4 and may therefore be rejected. A scheme leading to a complex of formula AD_3:

$$A + 3D \underset{k_b}{\overset{k_f}{\rightleftharpoons}} AD_3, \qquad (5)$$

is likewise excluded, since it leads to the relation

$$2{\cdot}303s = b^3k_f + k_b, \qquad (6)$$

whereas the plots of s against b^3 are found to be markedly curved. The same applies to the variant in which AD_2 is formed as in equation 2 and then undergoes further reaction with D in a rapid equilibrium $AD_2 + D \rightleftharpoons AD_3$. If the correct equation involves an integral power of b, it is certainly equation 1, corresponding to the scheme given in equation 2. Our results do not, however, rule out some fractional power of b such as 1·5, which would correspond to concurrent reactions giving AD and AD_2. Since such a scheme would lead to much greater complexity, we have not pursued it further.

In what follows we have adopted the scheme given in equation 2 for the overall reaction. It is not, however, necessary to suppose that AD_2 is formed by termolecular collisions. The kinetic equation 1 is equally consistent with a preliminary rapid equilibrium and a bimolecular rate-determining step, as in the following alternative schemes:

$$2D \overset{\text{Fast}}{\rightleftharpoons} D_2;\quad D_2 + A \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} AD_2, \tag{7}$$

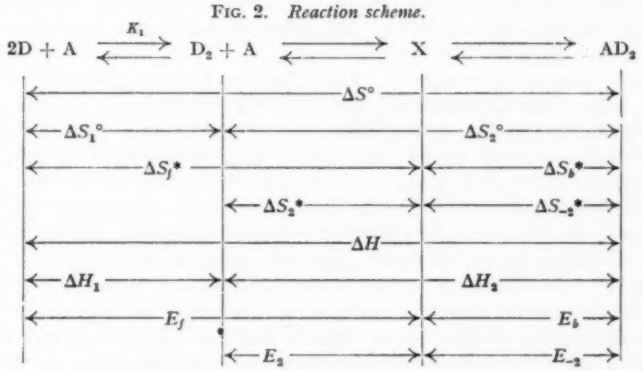
$$A + D \overset{\text{Fast}}{\rightleftharpoons} AD;\quad AD + D \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} AD_2, \tag{8}$$

Analysis shows that the forward rate constant k_f determined from the experimental results by means of equation 1 would then be equal to K_1k_2, where K_1 is the equilibrium constant $(D_2)/(D)^2$ or $(AD)/(A)(D)$; and the reverse rate constant k_b would be equal to k_{-2}. Intermediates of this kind are very commonly invoked to account for third-order kinetics.

Of the two possible intermediates, the complex D_2 seems not unlikely. There is evidence for some degree of association of diethylamine by hydrogen-bonding in the liquid phase; the frequency of the N–H stretching frequency is lower in liquid diethylamine than in the vapour,[11] and is shifted in solution in carbon tetrachloride and ethanol.[12] For the gas phase, the abnormally high values of the second virial coefficient have been interpreted in terms of dimerisation;[13] calculations on this basis gave, for $2D \rightleftharpoons D_2$, $\Delta H = -3{\cdot}3$ kcal. mole^{-1}, $\Delta S^0 = -20{\cdot}3$ cal. deg.$^{-1}$ mole^{-1}. The last figure is derived from values of K_p expressed in atm.; to convert the units into mole l.$^{-1}$, it is necessary to subtract 6·4, and we obtain $\Delta S^0 = -27$ cal. deg.$^{-1}$ mole^{-1}.

We therefore adopt the reaction scheme expressed in equation 7. Our general conclusions would, however, be unaffected if the scheme given in equation 8 were correct. The various quantities concerned in the equilibria and kinetics are shown in Fig. 2. Of these, the following have been experimentally determined (Table 3); ΔH, ΔS^0, E_f, ΔS_f^*, $E_b = E_2$, and $\Delta S_b^* = \Delta S_2^*$.

FIG. 2. *Reaction scheme.*



Interpretation of the Equilibrium Data.—The values of the overall standard entropy change ΔS^0 shown in Table 3 can be interpreted as follows in terms of the reaction scheme given in equation 7. The association of three molecules into one ($2D + A \longrightarrow AD_2$) would by itself lead to a considerable decrease of entropy (cf. the value −27 cal. deg.$^{-1}$ mole^{-1} derived above for $2D \longrightarrow D_2$ in the gas phase). The experimental value for acetone–water solutions, however, is +10 cal. deg.$^{-1}$ mole^{-1}, indicating that considerable

[11] Barr and Hazeldine, *J.*, 1955, 4169.
[12] Chulanovski, *Izvest. Akad. Nauk, U.S.S.R., Ser. Fiz.*, 1953, **17**, 624; *Chem. Abs.*, 1954, **48**, 5651.
[13] Lambert and Strong, *Proc. Roy. Soc.*, 1950, *A*, **200**, 566.

XUM

desolvation accompanies the complex-formation. The value in acetone–ether, −30 cal. deg.$^{-1}$ mole^{-1}, indicates that there is less desolvation of the reactants in this solvent.

The fact that there is considerably more complex-formation in acetone than in ethanol or propan-2-ol, although all these solvents have comparable dielectric constants, implies that some specific interaction is concerned. This presumably is the association of diethylamine with the solvents by hydrogen bonding; for acetone, there is independent evidence of this from infrared observations on the N–H stretching frequency.[14,15] (Related instances of equilibria not controlled by the dielectric constant are the associations of trinitrobenzene with naphthalene[16] and with dimethylaniline.[5]) Again, in acetone–water the complex-formation is considerably greater than in acetone–ether, in the temperature range used; here again the diethylamine is presumably preferentially solvated.

The overall enthalpy change ΔH will likewise include contributions due to desolvation, and the difference of $7{\cdot}5 \pm 2$ kcal. mole^{-1} between the values for acetone–ether and acetone–water represents the additional desolvation energy in the latter solvent. This is a reasonable value, corresponding roughly with the breaking of two N–H···O hydrogen bonds.[17]

Interpretation of the Kinetic Data.—The observed entropies of activation. The observed values of ΔS_b^* (Table 3) refer to the process $AD_2 \longrightarrow X$, where X is the transition complex in the reverse reaction $AD_2 \longrightarrow D_2 + A$ (see Fig. 2). It is striking that the values of ΔS_b^* in both solvents are large and negative (−20 and −42 cal. deg.$^{-1}$ mole^{-1}), although incipient dissociation of one molecule into two would be itself lead to a positive value. It must be inferred that the transition complex X is more solvated than AD_2; and there will be still more solvation as X goes over to the products $D_2 + A$. The difference between the two solvents is also interesting. For acetone–water, the value of ΔS_b^* is double that for acetone–ether, in accordance with the greater solvating power of acetone–water, which will lead to a greater difference of solvation between AD_2 and X.

The values of ΔS_f^*, which refer to the process $2D + A \longrightarrow D_2 + A \longrightarrow X$ (see Fig. 2), are negative, as might be expected from the decrease in the number of molecules. The value for acetone–water is considerably more positive than that for acetone–ether (−32 against −50 cal. deg.$^{-1}$ mole^{-1}); this indicates that considerably more desolvation occurs in acetone–water.

The observed energies of activation. The values of E_b or E_{-2}, for the reverse reaction $AD_2 \longrightarrow X$, reflect the interpretation given to ΔS_b^*. They will include terms for the dissociation of AD_2 and for solvation changes. The smaller value in acetone–water (4 against 7·7 kcal. mole^{-1}) reflects the greater heat of solvation in this solvent; the difference between the contributions from solvation is thus $3{\cdot}7 \pm 1{\cdot}6$ kcal. mole^{-1}. This is an appreciable fraction of E_b. Similar large contributions to E from solvation changes have been noted for other reactions.[18] The values of E_f, if our interpretation of ΔS_f^* is correct, will be influenced by the desolvation that accompanies the process $2D + A \longrightarrow D_2 + A \longrightarrow X$; the difference of $3{\cdot}8 \pm 0{\cdot}9$ kcal. mole^{-1} between the two solvents corresponds to the greater energy of desolvation required in acetone–water.

The individual steps of the reaction: kinetic and thermodynamic parameters. It is of interest to attempt estimates of the energy and entropy functions (see Fig. 2) for the individual reactions $2D \rightleftharpoons D_2$ (ΔH_1, ΔS_1^0) and $D_2 + A \longrightarrow X \longrightarrow AD_2$ (ΔH_2, E_2, ΔS_2^0, ΔS_2^*). In the following, singly primed quantities refer to acetone–ether as solvent and doubly primed to acetone–water.

The energy parameters may be estimated as regards order of magnitude from the

[14] Dodd and Stephenson, in "Hydrogen Bonding," ed. Hadži and Thompson, Pergamon Press, 1959, p. 177.
[15] Mizushima, Tsuboi, Shimanouchi, and Tsuda, *Spectrochim. Acta*, 1955, **7**, 106.
[16] Ross and Labes, *J. Amer. Chem. Soc.*, 1955, **77**, 4916.
[17] Pimentel and McClellan, "The Hydrogen Bond," Freeman, San Francisco and London, 1960, pp. 214, 224.
[18] Caldin, *J.*, 1959, 3345.

following considerations: (i) it is very unlikely that E_2 will be negative, since, although in the absence of solvation the formation of an outer complex may proceed with zero or small activation energy,[3b,3c] there will be a positive contribution from desolvation; and (ii) on account of desolvation, ΔH_1 will have a more positive value than that in the vapour phase (−3·3 kcal. mole^{-1}), as in the case of the analogous dimerisation of carboxylic acids.[19] Assuming then that (i) $E_2 > 0$ and (ii) $\Delta H_1 > (-3{\cdot}3)$ kcal. mole^{-1}, and using the relations (see Fig. 2) $\Delta H_2 = \Delta H - \Delta H_1$ and $E_2 = E_f - \Delta H_1$, we conclude that in acetone–ether E_2' lies between 0 and 3·5, $\Delta H_2'$ between −8·7 and −3·6, and $\Delta H_1'$ between −3·3 and +0·2 kcal. mole^{-1}. The values for the two solvents are collected in Table 4.

TABLE 4. *Estimated rate and equilibrium parameters for the individual reactions.*

(Entropies in cal. deg.$^{-1}$ mole^{-1} at 25°; energies in kcal. mole^{-1}.)

Reaction	Function	Solvent: Acetone–ether	Solvent: Acetone–water
$2D \longrightarrow D_2$	ΔH_1	−3·3 to +0·2	−3·3 to +4·1
	ΔS_1^0	*ca.* −17	*ca.* −7
$D_2 + A \longrightarrow AD_2$	ΔH_2	−8·7 to 3·6	−5·8 to +4·6
	ΔS_2^0	*ca.* −13	*ca.* +17
	E_2	0 to 3·5	0 to 7·4
	$E_{-2} = E_b$	7·7 ± 0·6	4 ± 1
	ΔS_2^*	*ca.* −33	*ca.* −25
	$\Delta S_{-1}^* = \Delta S_b^*$	−20 ± 3	−42 ± 4·5

Estimation of the entropy parameters is more difficult. In the gas phase, $\Delta S_1^0 = -27$ cal. deg.$^{-1}$ mole^{-1}, and in solution we may expect a less negative value on account of desolvation; thus we may conclude that $\Delta S_1^{0''} > \Delta S_1^{0'} > -27$ cal. deg.$^{-1}$ mole^{-1}. In the analogous dimerisation of acetic acid, which likewise involves hydrogen bonds, the standard entropy changes even in non-polar solvents exceed the gas-phase values by 10 cal. deg.$^{-1}$ mole^{-1} or more,[20] so this figure will not be too large for acetone–ether. We therefore take $\Delta S_1^{0'} = -17$ cal. deg.$^{-1}$ mole^{-1}. The relations (see Fig. 2) $\Delta S_2^0 = \Delta S^0 - \Delta S_1^0$ and $\Delta S_f^* = \Delta S_1^0 + \Delta S_2^*$ then lead to values of −13 cal. deg.$^{-1}$ mole^{-1} for $\Delta S_2^{0'}$ and −33 cal. deg.$^{-1}$ mole^{-1} for $\Delta S_2^{*'}$. This value $\Delta S_2^{*'}$ is of the right order for a bimolecular association, and to this extent justifies the estimate used for $\Delta S_1^{0'}$; a higher estimate than 10 cal. deg.$^{-1}$ mole^{-1} for the desolvation contribution to $\Delta S_1^{0'}$ would make $\Delta S_2^{*'}$ unduly high.

In view of the higher solvating power of acetone–water than of acetone–ether, it is natural to suppose that $\Delta S_1^{0''} > \Delta S_1^{0'}$; thus our estimate of the desolvation contribution to $\Delta S_1^{0''}$ must be at least 10 cal. deg.$^{-1}$ mole^{-1}. On the other hand, the same principle requires that $\Delta S_2^{*''}$ be more positive than $\Delta S_2^{*'}$, and this entails that the contribution to $\Delta S_1^{0''}$ does not exceed 28 cal. deg.$^{-1}$ mole^{-1} (if the contribution to $\Delta S_1^{0'}$ is 10). As a compromise we may tentatively adopt the value 20 cal. deg.$^{-1}$ mole^{-1}; we then obtain the values $\Delta S_2^{0''} = +17$ and $\Delta S_2^{*''} = -25$ cal. deg.$^{-1}$ mole^{-1}.

The values relating to the separate dimerisation and complex-formation reactions are collected in Table 4. It will be seen that they are self-consistent and reasonable values for association accompanied by some desolvation, the desolvation effects being greater in acetone–water. No great reliance, however, can be placed on the absolute values of these tentative estimates. The possibility of a positive value of E_2 for the complex-formation is interesting, since it would be attributable mainly to the energy required for desolvation, as for the complex-formation between trinitrobenzene and ethoxide ion.[18]

Comparison with the Rates of Reaction of Trinitrobenzene with Aromatic Amines.—It is noteworthy that, in contrast to the reaction with diethylamine, the rates of formation of the complexes between trinitrobenzene and various aromatic amines were too fast for measurement (Table 1). The explanation may be that only the diethylamine reaction goes *via* the dimer, whose concentration is probably low; the observed 1 : 1 stoicheiometry

[19] Allen and Caldin, *Quart. Rev.*, 1953, **7**, pp. 272 *et seq.*
[20] Davies, Jones, Patnaik, and Moelwyn-Hughes, *J.*, 1951, 1249.

XUM

of the complexes with aromatic amines [5] suggests that their formation will follow equation 3 rather than 2. It may be, however, that the reaction with the diethylamine dimer has the higher activation energy also. If the reactions with aromatic amines are bimolecular, the kinetic observations imply that their energies of activation are less than about 5·5 kcal. mole^{-1}; it is thus possible that these energies of activation are less than that for the diethylamine reaction (E_2 in Table 4).

General Conclusions on the Reaction of Trinitrobenzene with Diethylamine.—(i) The reaction is reversible. In the forward direction it appears to follow third-order kinetics, first-order in trinitrobenzene and second-order in diethylamine. This is interpreted in terms of a rapid preliminary equilibrium, possibly the dimerisation of diethylamine. (ii) The entropy and energy parameters derived from the observed rate and equilibrium constants suggest that desolvation occurs progressively in the several stages of the forward reaction. Solvation changes are greater in acetone–water than in acetone–ether, as would be expected if solvation were due to hydrogen bonding. (iii) Of the rate and equilibrium parameters for the association reaction $D_2 + A \rightleftharpoons AD_2$ (or possibly $D + AD \rightleftharpoons AD_2$) only those derived from the rates of the reverse reaction can be directly determined (E_{-2} and $\Delta S_{-2}^{\ddagger}$). The rest can be given reasonable values of varying reliability. The values of E_{-2} show that considerable contributions are made by changes of solvation.

We thank D.S.I.R. for research studentships to C. R. A. and A. J. B.; and Dr. R. Foster for helpful discussions and for communication of results before publication.

Department of Physical Chemistry,
The University, Leeds 2.
Chemistry Department,
Queen's College, Dundee.

[*Received, November 23rd,* 1960.]

---

414. *Synthesis of* 4-O-(β-D-*Glucopyranosyl*)-D-*ribitol, a Degradation Product of the Ribitol Teichoic Acid from the Walls of* Bacillus subtilis.

By J. Baddiley, J. G. Buchanan, and F. E. Hardy.

4-*O*-(β-D-Glucopyranosyl)-D-ribitol, a degradation product of the teichoic acid from *Bacillus subtilis* walls, has been synthesised by a Koenigs–Knorr reaction from tetra-*O*-acetyl-α-D-glucopyranosyl bromide and 5-*O*-benzyl-2,3-*O*-isopropylidene-1-*O*-triphenylmethyl-D-ribitol. Evidence is presented that no migration of protecting groups occurred during the synthesis, and an explanation is offered for a migration observed in a synthesis of *O*-galactosyl-glycerols.

Teichoic acids, polymeric esters of phosphoric acid, are present in the walls and cell contents of a number of bacteria.[1-4] Hydrolysis of the wall teichoic acid from *Bacillus subtilis* with alkali, followed by enzymic dephosphorylation, gives 4-*O*-(β-D-glucopyranosyl)-D-ribitol.* On the basis of this and other evidence, a structure has been assigned to the teichoic acid.[5,6] A synthesis of the phosphorus-free degradation product was desirable.

Since the glucoside has a β-configuration, a possible synthesis entails reaction between

* Equivalent name: 2-*O*-(β-D-glucopyranosyl)-L-ribitol. Cf. *J.*, 1957, 1870, footnote.

[1] Armstrong, Baddiley, Buchanan, Carss, and Greenberg, *J.*, 1958, 4344.
[2] Baddiley, *Proc. Chem. Soc.*, 1959, 177.
[3] Armstrong, Baddiley, Buchanan, Davison, Kelemen, and Neuhaus, *Nature*, 1959, **184**, 247.
[4] Baddiley and Davison, *J. Gen. Microbiol.*, 1961, **24**, 295.
[5] Armstrong, Baddiley, and Buchanan, *Nature*, 1959, **184**, 248.
[6] Armstrong, Baddiley, and Buchanan, *Biochem. J.*, 1960, **76**, 610.

XUM

tetra-*O*-acetyl-α-D-glucopyranosyl bromide and a suitably protected ribitol derivative.[7,8] Koenigs–Knorr reactions between glycosyl halides and secondary alcohols do not normally give high yields of the required glycosides; nevertheless, the method has been used in rational syntheses of several disaccharides.[7,9,10] The required derivative of ribitol should have only the 4-hydroxyl group (D-form) free. Since ribitol itself is a *meso*-form it was necessary to use as starting material an optically active derivative, such as D-ribose or D-ribonolactone. A similar situation arose in the synthesis of cytidine diphosphate ribitol and its degradation products.[11]

D-Ribonolactone (I) was converted into 2,3-*O*-isopropylidene-D-ribitol (IV) by reduction of the isopropylidene-lactone (II) with lithium aluminium hydride.[12] Triphenylmethylation gave the crystalline 1,5-di-*O*-triphenylmethyl ether (V), further characterised as its crystalline 4-benzoate. Condensation of tetra-*O*-acetylglucosyl bromide with the ether (V) in benzene solution in the presence of silver carbonate, iodine, and anhydrous calcium sulphate, gave a product which was deacetylated catalytically in methanol. The crystalline starting material (V) was recovered in 76% yield. The remaining product was partitioned between water and chloroform to extract water-soluble compounds, and the chloroform-soluble portion, presumably containing the glucoside (X), was hydrolysed with acid to remove triphenylmethyl and isopropylidene groups. Paper chromatography showed the presence of ribitol and two compounds having R_F values close to that of the required glucoside. Chromatography on charcoal–Celite gave a fraction containing the two monoglucosides free from other material. This mixture had the following properties: (*a*) one component had an R_F value identical with that of the glucoside from the teichoic acid; (*b*) the mixture was completely hydrolysed to ribitol and glucose by a crude emulsin preparation known not to hydrolyse α-glucosides; (*c*) the mixture, after successive oxidation with sodium periodate, reduction with sodium borohydride, and hydrolysis with acid, gave both ethylene glycol and glycerol.[13] It appeared, therefore, that the synthesis had yielded small amounts of D-ribitol 4-β-D-glucoside and D- or L-ribitol 1-β-D-glucoside. The latter must have arisen through loss of one or other of the two triphenylmethyl groups during the condensation. Such a reaction has been used recently by Bredereck and his co-workers in the synthesis of disaccharides from triphenylmethyl ethers and glycosyl halides in the presence of silver perchlorate.[14] Under the conditions used here loss of a triphenylmethyl group with simultaneous glycosylation might be favoured through steric hindrance of the 4-hydroxyl group in the ether (V) by the bulky triphenylmethyl group at the 5-position.

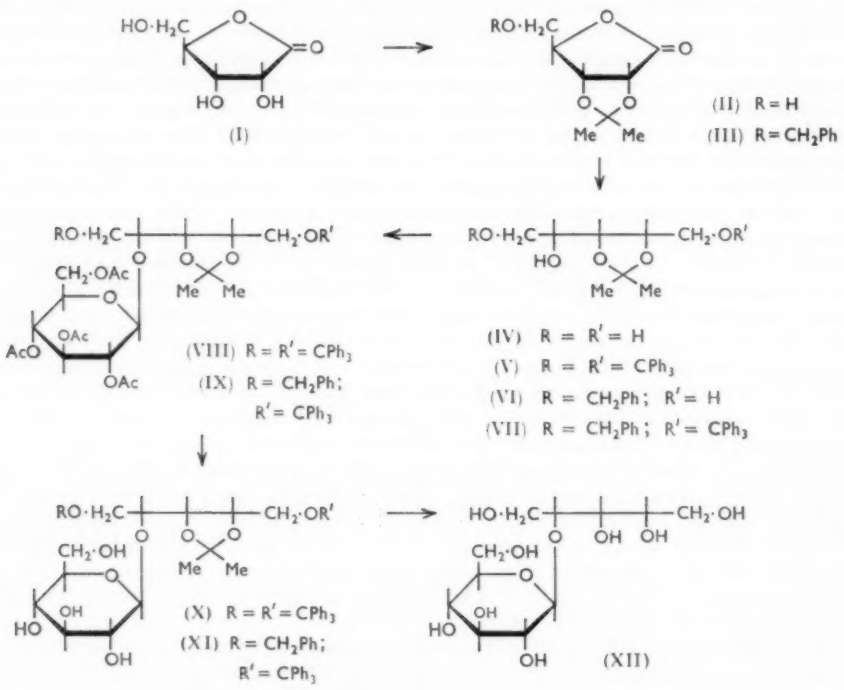
Three points were clear from the unsuccessful synthesis: (i) β-glucosides were formed; (ii) the isopropylidene group was retained throughout the condensation, since no 3-glucoside, which would be readily detected on chromatograms by its yellow colour with the periodate–Schiff reagents,[15] was found; (iii) no acid-catalysed migration of isopropylidene group had taken place, since the recovered starting material retained its full optical activity. In view of the limited success of these experiments it was decided to prepare the *O*-benzyl ether (VII), and to examine its reaction with the glucosyl bromide.

The *O*-isopropylideneribonolactone (II) was treated with benzyl bromide and silver oxide in dimethylformamide according to Croon and Lindberg's procedure.[16] Hough, Jones, and Mitchell [12] have shown that methylation of this lactone by Purdie's method gave the 5-*O*-methyl ether without opening of the lactone ring. The benzyl ether was

[7] Evans, Reynolds, and Talley, *Adv. Carbohydrate Chem.*, 1951, **6**, 27.
[8] Haynes and Newth, *Adv. Carbohydrate Chem.*, 1955, **10**, 207.
[9] Bächli and Percival, *J.*, 1952, 1244.
[10] Aspinall and Ferrier, *J.*, 1958, 1501.
[11] Baddiley, Buchanan, and Fawcett, *J.*, 1959, 2192.
[12] Hough, Jones, and Mitchell, *Canad. J. Chem.*, 1958, **36**, 1720.
[13] Viscontini, Hoch, and Karrer, *Helv. Chim. Acta*, 1955, **38**, 642.
[14] Bredereck, Wagner, Faber, Ott, and Rauther, *Chem. Ber.*, 1959, **92**, 1135.
[15] Archibald, Baddiley, and Buchanan, *Biochem. J.*, in the press.
[16] Croon and Lindberg, *Acta Chem. Scand.*, 1959, **13**, 593.

XUM

purified by chromatography on silica and the resulting syrup, which was homogeneous on paper chromatography, was purified further by distillation; it was characterised as the crystalline cyclohexylamide. Reduction by lithium aluminium hydride afforded the *O*-benzylribitol (VI) as a chromatographically homogeneous syrup; hydrogenolysis of the latter gave a single compound shown by chromatography to be 2,3-*O*-isopropylideneribitol (IV). Triphenylmethylation of the ether (VI) gave the required benzyl triphenylmethyl ether (VII), conveniently isolated as its 4-acetate and regenerated therefrom by deacetylation.



The Koenigs–Knorr reaction was carried out as before giving, after deacetylation and chromatography on neutral alumina, a solid with the properties of the *O*-benzyl-*O*-glucosyl-*O*-isopropylidene-*O*-triphenylmethylribitol (XI) in 7·5% yield. Removal of protecting groups by hydrogenolysis and acid-hydrolysis gave 4-*O*-(β-D-glucopyranosyl)-D-ribitol (XII), identical with that obtained from the *B. subtilis* teichoic acid.[5,6]

The infrared spectrum of the synthetic glucoside, which had crystallised from anhydrous methanol–ether, differed appreciably from that of the glucoside from the teichoic acid.[6] The latter glucoside has since been found [17] to be a hemihydrate, and when it was recrystallised from methanol–ether the infrared spectra of the synthetic and the " natural " compound were identical. The spectrum of the hemihydrate shows a characteristic hydrate maximum [18] at 1634 cm.$^{-1}$, and Dr. Lewis J. Sargent in this laboratory has found similar differences in the infrared spectra of crystalline cellobiitol and its hydrate when measured from KBr discs. Comparison was made of m. p.s, infrared spectra and specific rotation of

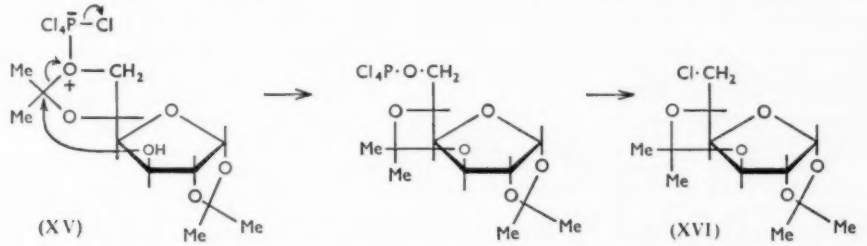
[17] Armstrong, Baddiley, and Buchanan, *Biochem. J.*, in the press.
[18] Colbran, Guthrie, and Parsons, *J.*, 1960, 3532.

XUM

the glucosides and their crystalline octa-acetates. Paper chromatograms of the glucosides and their partial acid-hydrolysates were identical.

In the second synthesis there was no indication of the formation of a 1-*O*-glucosylribitol derivative. However, it is possible that traces of this compound and a corresponding amount of triphenylmethanol were formed,[14] the former being lost during washing of chloroform solutions with water.

In a Koenigs–Knorr reaction in chloroform, with silver oxide in the place of silver carbonate, Wickberg[19] observed apparent isomerisation of optically active 1,2-*O*-isopropylidene-L-glycerol due to migration of the isopropylidene group. In reaction with



tetra-*O*-acetyl-α-D-galactopyranosyl bromide both 1-L- and 1-D-glycerol isomers were produced. We have obtained no evidence for such isomerisation in our reactions. In the first synthesis through the di-*O*-triphenylmethyl ether (V) the recovered starting material had unaltered optical activity; acid-catalysed migration of the isopropylidene residue would have caused racemisation. In the second synthesis, some of the starting material (VII) which was recovered by chromatography was hydrogenolysed and triphenylmethylated. The resulting ether (V) possessed the correct optical activity, and therefore we are confident that the synthetic glucoside is the 4-*O*-glucosyl-D-ribitol isomer.

The extensive racemisation observed by Wickberg[19] may be related to his isopropylidene compound's being derived from a primary alcohol. By a mechanism similar to that proposed for the acetolysis of acetals,[20] the co-ordination of the carbonium ion (G^+) derived from the glycosyl halide to the ketal-oxygen atom can be envisaged as in (XIII) ⟶ (XIV). This would proceed in addition to the normal Koenigs–Knorr glycosylation of the free hydroxyl group and lead to the formation of a mixture of isomers. In the ribitol derivatives (V) and (VII) both ketal-oxygen atoms are relatively hindered and so could not easily form similar co-ordination compounds. This view was confirmed by acetylation of the mother-liquors from crystallisation of the synthetic glucosylribitol; only the octa-acetate previously prepared from a crystalline sample of the glucoside was detected.

A similar mechanism may explain the formation of 6-chloro-6-deoxy-1,2:3,5-di-*O*-isopropylidene-α-D-glucose (XVI) from 1,2:5,6-di-*O*-isopropylidene-α-D-glucose (XV) and phosphorus pentachloride.[21]

This scheme seems preferable to that proposed by Smith.[21]

[19] Wickberg, *Acta Chem. Scand.*, 1958, **12**, 1187.
[20] Bourne, Burdon, and Tatlow, *J.*, 1958, 1274; 1959, 1864.
[21] Smith, *J.*, 1956, 1244.

XUM

Experimental

Infrared spectra were determined on potassium bromide discs. Silica gel (British Drug Houses) or neutral alumina (Grade O alumina neutralised with acetic acid and reactivated) were used for chromatography.

Paper Chromatography.—Whatman No. 1 or No. 4 paper was used. The following solvent systems were used by descending irrigation: (A) Butan-1-ol–ethanol–water (5 : 1 : 4). (B) Butan-1-ol–ethanol–water–ammonia (*d* 0·88) (40 : 10 : 49 : 1).[22] (C) Butan-1-ol–ethanol–water (4 : 1 : 1). (D) Di-isopropyl ether on paper treated with dimethyl sulphoxide.[23] (E) Light petroleum (b. p. 60—80°) on paper treated as in (D).[23]

All compounds containing α-glycol groups were detected with the periodate–Schiff reagents,[24] and those containing isopropylidene groups by the periodic acid–Schiff reagents.[25] Triphenylmethyl ethers were detected with perchloric acid.[26]

2,3-O-*Isopropylidene*-D-*ribitol.*—This was prepared from D-ribonolactone.[12] It was chromatographically homogeneous in solvent A (R_P 0·71), and gave ribitol and anhydroribitol on acid hydrolysis.

2,3-O-*Isopropylidene*-1,5-*di*-O-*triphenylmethyl*-D-*ribitol.*—The above acetal (0·75 g.) was treated with triphenylmethyl chloride (2·6 g., 2·4 mol.) in pyridine (5 c.c.) for 3 days at room temperature. Isolated by use of chloroform, and crystallised from ethanol, the *ether* (2·1 g., 80%) had m. p. 170—171°, $[\alpha]_D^{24}$ +17·2° (*c* 4·1 in C_6H_6) (Found: C, 81·3; H, 6·7. $C_{46}H_{44}O_5$ requires C, 81·7; H, 6·5%). In solvent E it had R_P 0·88 (triphenylmethanol had R_P 0·23). It gave a crystalline *benzoate*, m. p. 87—89° from ethanol, when treated with benzoyl chloride in pyridine (Found: C, 81·2; H, 6·1. $C_{53}H_{48}O_6$ requires C, 81·6; H, 6·2%).

Koenigs–Knorr Reaction with 2,3-O-*Isopropylidene*-1,5-*di*-O-*triphenylmethyl*-D-*ribitol.*—The above ether (1·44 g.) was dissolved in pure, dry benzene (15 c.c.), anhydrous calcium sulphate (heated at 240—270° for 2·5 hr.; 3·5 g.) and silver carbonate (1·5 g.) were added, and the mixture was shaken vigorously for 12 hr. Iodine (0·2 g.) was added and a solution of tetra-*O*-acetyl-α-D-glucopyranosyl bromide (0·9 g., 1·03 mol.) in benzene (7 c.c.) was introduced during 30 min. with constant shaking in the dark. The shaking, with occasional release of carbon dioxide from the flask, was continued for 80 hr.[9] The mixture was filtered through "Hyflo Supercel" silica, and the filtrate extracted twice with water and evaporated to dryness. The residue was dissolved in methanol (25 c.c.), sodium methoxide (from 0·015 g. of sodium) in methanol (15 c.c.) added, and the mixture shaken for 6 hr. The crystals which separated (1·0 g.) were filtered off and identified as starting material (V) by specific rotation, $[\alpha]_D^{22}$ +17·1° (*c* 5·0 in C_6H_6), m. p., and infrared spectra. The filtrate was neutralised (solid carbon dioxide) and evaporated to dryness. The residue was shaken with a mixture of chloroform and water. Evaporation of the chloroform layer gave a syrup (0·5 g.) which was heated under reflux with acetone (50 c.c.) containing 2N-sulphuric acid (1·5 c.c.) for 4 hr. Water (20 c.c.) and 2N-sulphuric acid (1 c.c.) were added and heating was continued for 1 hr. The solution was neutralised by barium carbonate, and triphenylmethanol precipitated by addition of water. After filtration, the solution was evaporated to a syrup (0·15 g.). Chromatography in solvent B showed a complex mixture containing mainly ribitol and two components with R_P values in the ribitol monoglucoside region. The faster spot had the same $R_{ribitol}$ (0·58) as the glucoside from the teichoic acid; the slower spot had $R_{ribitol}$ 0·50. This crude product was chromatographed on a carbon–Celite column (from 12 g. of Norit A and 7 g. of Celite-545).[27] Elution with 5% ethanol gave a chromatographically pure syrup (0·02 g.) containing the two glucosides.

Action of β-*Glucosidase.*—A sample (1 mg.) of the above mixture in water (30 μl.) was incubated with a 1% solution of β-glucosidase (L. Light and Co.) (30 μl.) at 37° for 3 days under toluene. Chromatography of the product in solvent B showed that both glucosides had been completely hydrolysed and that the only products were glucose and ribitol.

Periodate Oxidation and Borohydride Reduction.[13]—The above ribitol glucosides (1·7 mg.)

[22] Hirst, Hough, and Jones, *J.*, 1949, 928.
[23] Wickberg, *Acta Chem. Scand.*, 1958, **12**, 615.
[24] Baddiley, Buchanan, Handschumacher, and Prescott, *J.*, 1956, 2818.
[25] Buchanan, Dekker, and Long, *J.*, 1950, 3162.
[26] Applegarth and Buchanan, *J.*, 1960, 4706.
[27] Zilliken, Rose, Braun, and Gyorgy, *Arch. Biochem. Biophys.*, 1955, **54**, 392.

XUM

and sodium metaperiodate (9 mg.) were dissolved in water (0·1 c.c.) and kept in the dark overnight. Sodium borohydride (10 mg.) was added and the solution kept overnight. 3N-Hydrochloric acid (0·1 c.c.) was added and the solution was boiled for 15 min. The product was chromatographed on paper in ethyl acetate–pyridine–water (7 : 2 : 1). Two spots with R_F 0·43 and 0·55, corresponding to glycerol and ethylene glycol respectively, were observed when the paper was sprayed with the periodate–Schiff reagents.

5-O-*Benzyl*-2,3-O-*isopropylidene*-D-*ribono*-1,4-*lactone*.—2,3-*O*-Isopropylidene-D-ribonolactone (1 g.) was dissolved in anhydrous dimethylformamide (30 c.c.), and purified benzyl bromide (5·5 c.c.) was added. Silver oxide (6 g.) was introduced during 60 min. with vigorous stirring which was continued for 16 hr. (cf. ref. 16). The mixture was filtered, the brown residue being washed with dimethylformamide (25 c.c.) and then chloroform (25 c.c.), and 1% potassium cyanide solution (250 c.c.) was added to the combined filtrate. The mixture was extracted with chloroform (3 × 50 c.c.), and the chloroform solution washed with water, dried (Na_2SO_4), and evaporated to a syrup. Most of the excess of benzyl bromide was removed by distillation at 90°/0·05 mm. Last traces were removed by quaternisation with pyridine (3·5 c.c.) overnight. The product was re-isolated with chloroform to give a syrup (2·2 g.) which was chromatographed on silica gel (60 g.). Benzene eluted dibenzyl ether and benzaldehyde, and benzene–ether eluted the required *lactone* (1·4 g.), which was homogeneous by paper chromatography. It was distilled at 125—135° (bath-temp.)/10^{-5} mm. and had n_D^{22} 1·5065, $[\alpha]_D^{23}$ −39·6° (*c* 1·1 in EtOH) (Found: C, 64·6; H, 6·6. $C_{15}H_{18}O_5$ requires C, 64·8; H, 6·5%). In solvent C, it had R_F 0·96 (ribonolactone had R_F 0·42; 2,3-*O*-isopropylideneribonolactone had R_F 0·80).

The lactone (0·34 g.) was treated with cyclohexylamine (2·5 c.c.) at 100° for 2 hr. and then at 50° overnight (cf. ref. 28). The *cyclohexylamide*, m. p. 63—65°, was isolated by using chloroform and crystallised from light petroleum (b. p. 60—80°) (Found: C, 66·8; H, 8·4. $C_{21}H_{31}O_5N$ requires C, 66·9; H, 8·2%).

5-O-*Benzyl*-2,3-O-*isopropylidene*-D-*ribitol*.—The preceding lactone (1 g.) in tetrahydrofuran (17 c.c.) was added dropwise to a suspension of lithium aluminium hydride (0·5 g.) in tetrahydrofuran (17 c.c.). The mixture was heated under reflux for 8 hr. Ethyl acetate (2 c.c.) was added with cooling and stirring, followed by 90% ethanol (75 c.c.). The precipitate was removed by centrifugation and washed with two volumes of ethanol. The combined centrifugates were evaporated to dryness and the residue was extracted with hot chloroform (3 × 70 c.c.). The combined chloroform solutions were washed with water, dried, and evaporated to a syrup (1 g.) which was chromatographically homogeneous (R_F 0·90 in solvent A).

The benzyl ether (0·1 g.) was hydrogenated for 20 hr. over palladium (from 0·1 g. of oxide) in ethanol (20 c.c.). Chromatography in solvent A showed that 2,3-*O*-isopropylideneribitol was the only product.

4-O-*Acetyl*-5-O-*benzyl*-2,3-O-*isopropylidene*-1-O-*triphenylmethyl*-D-*ribitol*.—5-*O*-Benzyl-2,3-*O*-isopropylidene-D-ribitol (0·75 g.) was treated with triphenylmethyl chloride (0·8 g., 1·05 mol.) in pyridine (5 c.c.) for 4 days at room temperature. The syrupy product (1·5 g.) was isolated in the same way as the previous di-*O*-triphenylmethyl ether. When examined on paper in solvent D it was found to contain triphenylmethanol together with a major component with $R_{triphenylmethanol}$ (written R_t below) 1·25. The syrup was acetylated with acetic anhydride (7 c.c.) in pyridine (10 c.c.), and the products were isolated by using benzene. When crystallised from ethanol the *acetate* (0·8 g., 54%) had m. p. 112—114° (Found: C, 76·6; H, 7·0. $C_{36}H_{38}O_6$ requires C, 76·3; H, 6·7%).

5-O-*Benzyl*-2,3-O-*isopropylidene*-1-O-*triphenylmethyl*-D-*ribitol*.—The above acetate (0·32 g.) was deacetylated catalytically with sodium methoxide in methanol. Crystallisation from aqueous methanol gave the *ether* (0·28 g.), m. p. 52—54°. Recrystallised from methanol it had m. p. 53—55°, $[\alpha]_D^{22}$ +20·3° (*c* 4·1 in C_6H_6) (Found: C, 75·6; H, 7·1. $C_{34}H_{36}O_5,CH_3{\cdot}OH$ requires C, 75·5; H, 7·2%). This compound could not be crystallised from acetone or acetone–water. In solvent D it had R_t 1·25 and in E it had R_F 0·73 (triphenylmethanol had R_F 0·23).

Koenigs–Knorr Reaction with 5-O-*Benzyl*-2,3-O-*isopropylidene*-1-O-*triphenylmethyl*-D-*ribitol*.—The last-mentioned ether (2·0 g.) was treated with tetra-*O*-acetyl-α-D-glucopyranosyl bromide (1·8 g., 1·15 mol.) in benzene (30 c.c.) in the presence of silver carbonate (3·0 g.), anhydrous calcium sulphate (7·0 g.), and iodine (0·35 g.), the technique being the same as before.

[28] Baddiley and Thain, *J.*, 1951, 246.

XUM

The product was deacetylated as before and, after neutralisation with solid carbon dioxide, was evaporated to dryness. A chloroform solution of the residue was washed with water and then saturated sodium chloride solution, then it was dried (K_2CO_3) and evaporated to a syrup (1·9 g.). Paper chromatography in solvent D showed the presence of three triphenylmethyl derivatives: a small amount of triphenylmethanol, a major quantity of starting material, and a compound with R_P 0·01. The mixture was chromatographed on neutral alumina (90 g.). Benzene and benzene–chloroform eluted the first two components; elution with chloroform–methanol (95 : 5) gave the third component (XI) (0·2 g., 7·5%) chromatographically pure, that crystallised (m. p. 80—82°) when triturated with light petroleum.

4-O-(β-D-*Glucopyranosyl*)-D-*ribitol*.—The above glucoside (0·2 g.) was hydrogenated over palladium (from 0·4 g. of oxide) in ethanol (40 c.c.) at atmospheric pressure for 60 hr. After removal of catalyst the solution was evaporated to dryness and the residue was heated in ethanol (47·5 c.c.) and N-sulphuric acid (2·5 c.c.) for 45 min. The solution was neutralised with barium carbonate and passed through Dowex-50 (NH_4^+) resin. After evaporation, the residue was shaken with water and chloroform, and the aqueous layer was examined chromatographically in solvent B. Only one compound was detected, having the same mobility as the glucoside from the *B. subtilis* teichoic acid. A mixture of the two ran as a single spot. The synthetic glucoside was purified further on a carbon–Celite column prepared from Norit A (20 g.) and Celite-545 (10 g.). Elution with 6% ethanol and evaporation gave the glucoside (0·06 g.). This was dissolved in a little methanol and ether was added to turbidity. The crystalline glucoside (0·02 g.), $[\alpha]_D^{22}$ −22° (*c* 1·0 in H_2O) had m. p. 134—137°, undepressed in admixture with the natural glucoside [6,17] (Found: C, 41·6; H, 7·0. Calc. for $C_{11}H_{22}O_{10}$: C, 42·0; H, 7·1%). The infrared spectra of the synthetic compound and the natural glucoside (which had been crystallised in the same way) were indistinguishable.

Acid Hydrolysis.—Samples (1·0 mg.) of the two glucosides were hydrolysed with 2N-hydrochloric acid at 100° for 9 hr. The hydrolysates were evaporated to dryness and chromatographed in solvent B. The hydrolysis products were identical, anhydroribitol, ribitol, glucose, and small amounts of acid-reversion products being detected.

4-O-(β-D-*Glucopyranosyl*)-D-*ribitol Octa-acetate*.—The glucoside (0·03 g.) was added to a mixture of acetic anhydride (1·5 c.c.) and pyridine (1·5 c.c.). After 2 days at room temperature the *acetate* was isolated with chloroform. It crystallised from ethanol or ether–light petroleum (b. p. 40—60°) as needles, m. p. 100°, $[\alpha]_D^{22}$ −14·1° (*c* 1·5 in $CHCl_3$) (Found: C, 49·7; H, 6·2. $C_{27}H_{38}O_{18}$ requires C, 49·8; H, 5·9%). The acetates derived from the synthetic and natural glucosides had the same m. p., were undepressed in admixture, possessed identical infrared spectra, and gave identical analytical figures.

Conversion of 5-O-*Benzyl*-2,3-O-*isopropylidene*-1-O-*triphenylmethyl*-D-*ribitol recovered from the Koenigs–Knorr Reaction into* 2,3-O-*Isopropylidene*-1,5-*di*-O-*triphenylmethyl*-D-*ribitol*.—The recovered syrupy starting material (VII) (0·35 g.) was hydrogenated in ethanol (35 c.c.) over palladium (from 0·6 g. of oxide) at atmospheric pressure for 24 hr. After filtration and evaporation the residue was treated with triphenylmethyl chloride (0·3 g.) in pyridine (4 c.c.) for 4 days. Isolated with chloroform, the syrupy product was chromatographed on alumina. Elution with chloroform gave a syrup (0·28 g.) which crystallised from methanol–water. It had m. p. 170—171°, $[\alpha]_D^{22}$ +17·5° (*c* 3·0 in C_6H_6). Its infrared spectrum was identical with that of the compound (V) prepared earlier.

This work was carried out during the tenure by one of us (F. E. H.) of a D.S.I.R. Studentship and later an I.C.I. Fellowship. We thank Roche Products Ltd. for a generous gift of ribonolactone, and the Medical Research Council and the Nuffield Foundation for financial support.

DEPARTMENT OF CHEMISTRY, KING'S COLLEGE,
UNIVERSITY OF DURHAM, NEWCASTLE UPON TYNE. [*Received, December 21st,* 1960.]

XUM

415. *Biformene.*

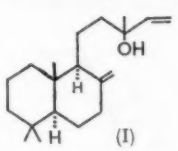
By R. M. Carman and P. K. Grant.

A new diterpene hydrocarbon, named biformene, has been isolated from *Dacrydium biforme* and its structure elucidated as (II).

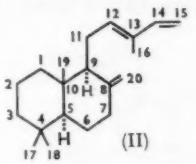
The heartwood extractives of *Dacrydium biforme* contain manool [1] (I), which comprises 90% of the neutral fraction. Reinvestigation of this wood has led to the isolation of a diterpene hydrocarbon for which the name biformene is proposed.

Biformene, obtained by the distillation of the mother-liquors from the recrystallization of manool, and purified by chromatography to constant ultraviolet absorption, is a colourless mobile oil with the formula $C_{20}H_{32}$. It is readily polymerized by heat or atmospheric oxygen. Its ultraviolet and infrared absorption indicated conjugated double bonds, an exocyclic methylene group, a vinyl group, and a *gem*-dimethyl group. On hydrogenation it gave a liquid hydrocarbon $C_{20}H_{38}$ which was saturated (infrared spectrum; ultraviolet end-absorption, $\varepsilon_{2100} < 200$). Biformene therefore has two rings and three double bonds. Reaction with maleic anhydride gave only a resin.

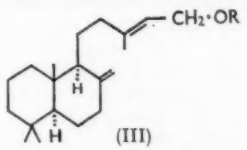
Vapour-phase chromatography of the crude selenium dehydrogenation product of biformene showed the presence of ten compounds, seven of which were identified as substituted naphthalenes by their ultraviolet absorption, the remaining three being substituted phenanthrenes. Addition of authentic materials to the crude dehydrogenation mixture and vapour-phase chromatography of these mixtures indicated three peaks as due to 1,7-dimethylphenanthrene, 1,2,5-trimethylnaphthalene, and 7-isopropyl-1-methylphenanthrene. The first two were isolated and fully characterized. Mixtures of naphthalenes and phenanthrenes have been obtained previously from the bicyclic diterpenes agathic acid,[2] manoyl oxide,[3] and an oxomanoyl oxide derivative,[4] all of which have the



(I)



(II)



(III)

carbon skeleton of (I). We have found that dehydrogenation of manool by selenium gives the same ten products, but in different proportions (see p. 2190). Biformene yields 50·6% of naphthalenes and 49·4% of phenanthrenes: manool gives 60·8% and 39·2%, respectively. These figures, together with the rather close correspondence of the yields for each of the ten compounds, suggest that biformene has the same carbon skeleton as manool. Spectral considerations then require biformene to have its three double bonds arranged as in (II).

With this clue we then found that dehydration of manool by acetic acid gave biformene, so proving the carbon skeleton of biformene together with the stereochemistry at positions 5, 9, and 10. The known allyl acetate [5,6] (III; R = Ac), resulting from rearrangement of manoyl acetate, was also isolated; on alkaline hydrolysis this gave the corresponding allyl alcohol (III; R = H). Further proof of the carbon skeleton of biformene was provided when its hydrochloride was found to be identical with the trihydrochloride from manool.[1,7]

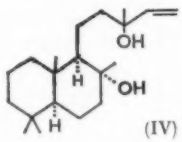
[1] Hosking and Brandt, *Ber.*, 1935, **68**, 1311.
[2] Ruzicka and Hosking, *Helv. Chim. Acta*, 1930, **13**, 1402.
[3] Hosking and Brandt, *Ber.*, 1935, **68**, 37.
[4] Hosking and Brandt, *Ber.*, 1935, **68**, 286.
[5] Büchi and Biemann, *Croat. Chem. Acta*, 1957, **29**, 163.
[6] Ohloff, *Annalen*, 1958, **617**, 134.
[7] Carman, unpublished result.

XUM

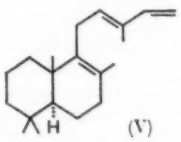
The ready dehydration of manool to biformene allowed the possibility that biformene is not present in the wood, but is an artefact of the working-up. The ultraviolet spectrum of an extract of the wood obtained by spectroscopically pure iso-octane at room temperature showed a strong inflexion at 2280 Å which is assigned to biformene, on a band with a maximum at 2320 Å. Chromatography over alumina indicated that both these bands were due to non-polar hydrocarbons. The optical density of the 2280 Å band corresponded to approximately 0·06% of biformene in the wood.

A similar hydrocarbon (V) was postulated by Ruzicka *et al.*[8] as a hypothetical, first-stage, dehydration product in the acetylation of sclareol (IV). Conformational analysis requires modification of this structure to (II), since the elimination of water from the 8α-hydroxyl group of sclareol demands *trans*-elimination,[9] resulting in an exocyclic 8-methylene group. That the exocyclic double bond does not isomerize to the endocyclic position under these conditions is demonstrated by the isolation of the allyl alcohol (III; R = H) and manool from sclareol.[6] Büchi and Biemann[5] reported the presence of a triene containing a conjugated diene system as an impurity formed on hydrolysis of sclareol diacetate and on dehydration of sclareol with acetic anhydride; from the infrared (not quoted) and ultraviolet spectra ($\lambda_{max.}$ 2280 Å; log ε 4·08) the hydrocarbon was considered to be a mixture of (II) and (VI).

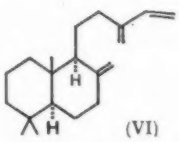
By acetylation and subsequent hydrolysis of sclareol, Ohloff[6] obtained a bicyclic triene, sclarene, which he formulated as (VI) and characterized as a dihydrochloride, m. p. 123—125°. Its physical constants closely resembled those of biformene but its infrared spectrum showed considerable C–O stretching in the 1050—1150 cm.$^{-1}$ region. When we repeated Ohloff's work we obtained the same products but in different yields, notably 30% of the bicyclic triene and 28% of epimanoyl oxide as against 47% and 6·4% respectively reported by Ohloff. The infrared spectrum of our liquid hydrocarbon from sclareol was identical with that of biformene and contained no C–O stretching absorption; and it gave the same saturated trihydrochloride as was prepared from manool, and not an unsaturated dihydrochloride.



(IV)



(V)



(VI)

Structure (II) is assigned to biformene in preference to Ohloff's formula (VI) for the following reasons. Structure (II), with the more stable trisubstituted double bond, should be formed in preference to (VI), which may in fact revert to (II) under acid conditions. The ultraviolet maximum at 2280 Å supports a disubstituted rather than a monosubstituted diene system [it should be noted, however, that ocimene, with a similar diene system, exhibits anomalous ultraviolet absorption[10] ($\lambda_{max.}$ 2350 Å; log ε 4·22)]. Finally, the nuclear magnetic resonance spectrum of biformene supports structure (II). The vinyl region of the spectrum (3·0—6·0 τ) had an integrated area corresponding to six protons which is in accord with structure (II), whereas (VI) requires seven protons. Two single proton peaks, at 5·25 and 5·50 τ, can be assigned to the two different exocyclic methylene protons;[11] these are unsplit, but broad, indicating that the coupling constants $J_{20,20'}$, $J_{7,20'}$ and $J_{9,20}$ are approximately zero. A triplet (relative area $\frac{1}{4}:\frac{1}{2}:\frac{1}{4}$ proton) centred at 3·36 τ ($J_{12,11}$ = 9·6 c./sec.) is assigned to the proton at $C_{(12)}$ while the $C_{(14)}$- and $C_{(15)}$-protons occur as a multiplet of eleven peaks (each of area approximately $\frac{1}{4}$ proton) between 3·68 and 5·07 τ. In addition, the spectrum showed four methyl peaks, at 9·18, 9·13, 9·13,

[8] Ruzicka, Engel, and Fischer, *Helv. Chim. Acta*, 1938, **21**, 364.
[9] Barton, Campos-Neves, and Cookson, *J.*, 1956, 3500.
[10] O'Connor and Goldblatt, *Analyt. Chem.*, 1954, **26**, 1726.
[11] Dev, *Tetrahedron*, 1960, **9**, 1.

and 8·27 τ: the three highest of these correspond to the unsplit 17-, 18-, and 19-methyl groups, while the peak at 8·27 τ must be due to an allylic methyl group,[12] thus confirming structure (II). The last peak is also broad, owing to secondary coupling with protons across the double bond.

It is proposed that the name biformene be given to the hydrocarbon of structure (II) while the name sclarene be reserved for the hydrocarbon (VI).

Experimental

M. p.s are corrected. Ultraviolet spectra were measured for iso-octane solutions. Alumina, B.D.H. grade " for chromatographic adsorption analysis," and light petroleum (b. p. 60—80°) were used unless otherwise stated.

Isolation of Biformene.—(*a*) Distillation of the neutral fractions of an acetone extract of *D. biforme* gave manool, b. p. 150—153°/0·3 mm. Distillation of the residue obtained from the mother-liquors from the recrystallization of manool gave a mobile straw-coloured oil, b. p. 140—145°/0·5 mm. Repeated chromatography on alumina from light petroleum gave *biformene*, n_D^{20} 1·5257, d_4^{20} 0·952, $[\alpha]_D^{20}$ +12·2° (*c* 14% in iso-octane) (Found: C, 87·4; H, 11·4. $C_{20}H_{32}$ requires C, 88·2; H, 11·8%), $\nu_{max.}$ (film) 1596 (C:C·C:C), 3079, 1786, 1644, and 888 (exocyclic CH_2=), 3034 infl., 990, 905 infl. (C:CH_2), 1388 and 1366 (*gem*-Me_2), also 1413 cm.$^{-1}$, $\lambda_{max.}$ 2280 Å (ε 15,300) (C:C·C:C). Redistillation resulted in decomposition. It was necessary to store biformene under a vacuum to minimize polymerization.

(*b*) *D. biforme* chips (10·4 g.) were treated with iso-octane (50 ml.) for 90 hr. at 20°. The extract, filtered and diluted to 10 times its volume, had $\lambda_{max.}$ 2320 Å (O.D. 0·82), $\lambda_{infl.}$ 2280 Å (O.D. 0·73). The extracted material, recovered at 20° and chromatographed over alumina from iso-octane, gave on elution with iso-octane a fraction still absorbing at 2280 and 2320 Å.

Synthesis of Biformene.—Manool (6·03 g.) in acetic acid (50 c.c.) was refluxed for ¾ hr. Chromatography on alumina from light petroleum gave, on elution with light petroleum, biformene (1·64 g.), n_D^{20} 1·5235, d_4^{20} 0·950 (Found: C, 88·45; H, 12·0%), $\nu_{max.}$ (film) 1642, 1592, 990, 905sh, and 890 cm.$^{-1}$, $\lambda_{max.}$ 2280 Å (ε 12,500). Further elution with light petroleum–ether (10 : 1) gave the allyl acetate (III; R = Ac) (2·3 g.), purified by distillation (bath-temp. 170°/0·15 mm.), n_D^{20} 1·5063 (lit.,[6] 1·5071) (Found: C, 79·3; H, 10·9. Calc. for $C_{22}H_{36}O_2$: C, 79·5; H, 10·9%), $\nu_{max.}$ (film) 1745 and 1232 (OAc), 1670 (CH:C), 3095, 1645, 889 (>C:CH_2) cm.$^{-1}$. Elution with light petroleum–ether (1 : 2) gave unchanged manool (1·23 g.).

The allyl acetate (1 g.) in 5% ethanolic potassium hydroxide (20 c.c.) was refluxed for 1 hr. Chromatography on alumina from light petroleum gave, on elution with light petroleum–ether (1 : 2) the allyl alcohol (III; R = H) which, purified by distillation (bath-temp. 180°/0·15 mm.), had n_D^{20} 1·5203 (lit.,[6] 1·5220), $\nu_{max.}$ (film) 3415 (OH), 1670 (CH:C), 1000 br (C–O), 3095, 1646, 887 (>C:CH_2) cm.$^{-1}$.

Sclareol (5 g.) was heated with acetic anhydride (5 g.) and acetic acid (5 g.) for 6 hr. (yield 4·81 g.) and then with alcoholic potassium hydroxide[6] (yield 4·57 g.). Chromatography on alumina from light petroleum gave biformene (1·47 g., 30%) on elution with light petroleum. Further elution with light petroleum–ether (30 : 1) gave colourless needles of epimanoyl oxide (1·41 g., 28%), m. p. and mixed m. p. 94—95° (from aqueous acetone).

Hexahydrobiformene.—Biformene (4·8 g.) in cyclohexane was hydrogenated (50°/100 atm.) over Raney nickel (activity W 2) for 12 hr. Chromatography on alumina from light petroleum gave a colourless oil (3·7 g.; ε_{2100} 1110). This oil, in light petroleum, was extracted with concentrated sulphuric acid (3 × 20 c.c.), washed with sodium carbonate and then water, chromatographed, and distilled (105°/0·02 mm.) to give *hexahydrobiformene*, n_D^{20} 1·4918, d_4^{20} 0·908, α_D^{20} +10·6° (homog.) (lit.,[6] 1·4922, 0·910, +44·1°) (Found: C, 86·5; H, 13·85. $C_{20}H_{38}$ requires C, 86·25; H, 13·75%). The infrared spectrum showed only C–C and C–H absorption. The ultraviolet spectrum had end-absorption only (ε_{2100} 190).

Dehydrogenation of Biformene.—Biformene (1·5 g.) was heated with selenium for 46 hr. at 310—320°. A benzene extract of the product was filtered through a Celite column and evaporated. The residue was filtered in light petroleum through a short alumina column. Vapour-phase chromatography (helium gas, 1 m. column of 15% silicone oil on chromosorb; 190°)

[12] Jackman, " Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," Pergamon Press, London, 1959, p. 58.

XUM

gave ten peaks (see Table). The peak at 1·35 is probably due to 7-ethyl-1-methylphenanthrene since the ultraviolet spectrum of this material was superimposable (as regards wavelengths) on that of pimanthrene.

Chromatography of the crude hydrocarbons (370 mg.) on alumina from light petroleum gave an oil (205 mg.); its 1,3,5-trinitrobenzoate, on repeated recrystallization gave 1,2,5-trimethylnaphthalene 1,3,5-trinitrobenzoate as yellow needles, m. p. 155—158° (lit.,[13] 158—159°) [Found: C, 59·0; H, 4·3; N, 10·9%; *M* (ref. 14), 378. Calc. for $C_{19}H_{17}N_3O_6$: C, 59·5; H, 4·5; N, 11·0%; *M*, 383]. Regeneration of the hydrocarbon on alkaline alumina gave 1,2,5-trimethylnaphthalene as plates (from aqueous ethanol), m. p. 29° (lit.,[2] 31—32°), $\lambda_{max.}$ 3240, 3154, 3092, 2944, 2886, 2780, 2308 Å (log ε 3·06, 2·84, 3·14, 3·73, 3·88, 3·80, 4·98) with infl. at 2992, 2968, 2834, 2685, 2588, 2250, 2177, 2138 Å (log ε 3·68, 3·70, 3·80, 3·59, 3·33, 4·51, 4·38) (this spectrum shows greater resolution than that reported in the literature [15]), $\nu_{max.}$ (film) 1601, 1515, 1442, 1414, 1381, 813, 791, 741 cm.$^{-1}$. The picrate, red needles from aqueous ethanol, had m. p. 136° (lit.,[13] 137—138°). Further elution of the hydrocarbon column with light petroleum gave a crystalline fraction (143 mg.), purified by sublimation (60°/0·02 mm.) and recrystallization from aqueous ethanol, to give 1,7-dimethylphenanthrene, m. p. 78—81° undepressed on admixture with pimanthrene (m. p. 82°) (recorded m. p. range from 75° [16] to 86° [17]). Its trinitrobenzoate (m. p. 155—158°) did not depress the m. p. of an authentic sample (m. p. 161°). The ultraviolet spectrum agreed with that reported.[18]

Dehydrogenation of Manool.—Manool (3 g.) was dehydrogenated with selenium as described for biformene. Vapour-phase chromatography gave ten peaks (see Table). Admixture of the dehydrogenation product with that from biformene and chromatography of the resultant mixture gave only the same ten peaks. Chromatography of the crude hydrocarbon fraction (630 mg.) on alumina from light petroleum gave an oil (440 mg.) from which 1,2,5-trimethylnaphthalene, m. p. 29°, was obtained as described above, giving one peak on vapour-phase chromatography at a relative retention time (pimanthrene = 1) of 0·27. The picrate had m. p. 135°. Further elution with light petroleum gave crystals (185 mg.), m. p. 79° (from aqueous ethanol), identified as 1,7-dimethylphenanthrene through the trinitrobenzoate (m. p. 158°), picrate (m. p. 129—130°, lit., 126°,[17] 132° [19]), and the ultraviolet spectrum.

Relative retention time (1,7-dimethylphenanthrene = 1)	Compound	Yield (%) from biformene	Yield (%) from manool
0·13	A substituted naphthalene	2·0	2·4
0·16	A substituted naphthalene		
0·24	1,2,5-Trimethylnaphthalene	12·1	13·5
0·49	A substituted naphthalene	0·2	0·2
0·65	A substituted naphthalene	0·3	0·4
0·73	A substituted naphthalene	0·4	0·5
1·00	1,7-Dimethylphenanthrene	12·3	9·5
1·10	A substituted naphthalene	1·9	2·2
1·35	A substituted phenanthrene	2·8	1·9
1·70	7-Isopropyl-1-methylphenanthrene	1·4	0·9
		33·4	31·5

Biformene Trihydrochloride.—Biformene (0·8 g.), suspended in glacial acetic acid, was shaken while dry hydrogen chloride was passed in at 20°. The solution became red after 90 min. Water was added after 6 hr. and the emulsion extracted with light petroleum. The yellow oil (660 mg.) crystallized. Repeated recrystallization from light petroleum gave the trihydrochloride as colourless needles, m. p. 123°, undepressed on admixture with manool trihydrochloride or with sclareol trihydrochloride, m. p. 125° (Found: C, 62·7; H, 9·4; Cl, 27·7. Calc. for $C_{20}H_{35}Cl_3$: C, 62·9; H, 9·2; Cl, 27·9%), ε_{2100} 175. The infrared spectrum (KBr) was completely superimposable on that of manool trihydrochloride or sclareol trihydrochloride, ν(major) 839, 740 cm.$^{-1}$.

[13] Ruzicka, Baumgarten, and Prelog, *Helv. Chim. Acta*, 1949, **32**, 2057.
[14] Godfrey, *Analyt. Chem.*, 1959, **31**, 1087.
[15] Heilbronner, Fröhlicher, and Plattner, *Helv. Chim. Acta*, 1949, **32**, 2479.
[16] Galik, Petrů, and Kuthan, *Tetrahedron*, 1959, **7**, 223.
[17] Brandt, *J. N. Z. Science Technol.*, 1952, **34***B*, 46.
[18] Heilbronner, Däniker, and Plattner, *Helv. Chim. Acta*, 1949, **32**, 1723.
[19] Haworth, Letsky, and Marvin, *J.*, 1932, 1784.

XUM

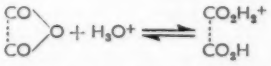
We thank Professor D. S. Tarbell and Dr. N. Sheppard for measuring nuclear magnetic resonance spectra, and Dr. G. Ohloff for a sample of epimanoyl oxide.

DOMINION LABORATORY, DEPARTMENT OF SCIENTIFIC & INDUSTRIAL RESEARCH,
WELLINGTON, NEW ZEALAND. [*Received, October 3rd,* 1960.]

416. *Cyclic Anhydrides in Sulphuric Acid.*

By J. A. LEISTEN.

It is shown that in the phthalic, maleic, and succinic systems the equilibrium:



is critically balanced in the region of 100% sulphuric acid, and that this finding is potentially important in the fundamental study of sulphuric acid. For the glutaric system the equilibrium lies far to the right even in the presence of a small excess of sulphur trioxide. Succinic anhydride is found to be a stronger base than phthalic and maleic anhydrides. Solvent mixtures are described which greatly increase the power of the cryoscopic method to solve problems of solute behaviour in sulphuric acid.

AT the outset of this work it was known that open-chain anhydrides extract water from 100% sulphuric acid and from dilute oleums.[1] Phthalic anhydride on the other hand was known from cryoscopic [2-4] and conductimetric [4] measurements largely to retain its identity in 100% sulphuric acid. (It was in fact the only weak base in this solvent to have been found among compounds composed of carbon, hydrogen, and oxygen.) It was not clear whether succinic anhydride ionises as a base or extracts water from the solvent; [4] and there was disagreement in the cryoscopic results reported for both phthalic acid and maleic acid.[2,5,6] Neverthless it appeared from these results that cyclic anhydrides and the related dicarboxylic acids do not always give the same products when dissolved in sulphuric acid. Either there are kinetic restrictions on the interconversion of the acid and anhydride in this solvent or the equilibrium

$$\text{anhydride} + \text{hydroxonium ion} \rightleftharpoons \text{acidium ion} \quad . \quad . \quad . \quad . \quad (1)$$

is critically balanced in that small range of concentration (99·5—100% sulphuric acid) in which cryoscopic measurements are made.

Cryoscopic results for phthalic, succinic, glutaric, and maleic acids and anhydrides are given below in terms of the van't Hoff *i*-value, which provides an estimate of the number of particles produced by each solute molecule in solution. Thus expressed, the results can be interpreted in broad outline. A finer analysis, though possible,[7] has not been attempted for a reason which appears later; but the freezing points and molalities of all the solutions are listed. The *i*-values for successive additions of a solute are calculated from the increments of molality and freezing-point depression. Where the carboxylic acid or anhydride is added to 100% sulphuric acid no *i*-value is calculated from the first addition, for this is the one most subject to error through the self-dissociation of the solvent. It should be remembered that this error can only reduce the *i*-value.

[1] Leisten, *J.*, 1955, 298.
[2] Hantzsch, *Z. phys. Chem.*, 1907, **61**, *A*, 257.
[3] Oddo and Casalino, *Gazzetta*, 1917, **47**, II, 232.
[4] Flowers, Gillespie, and Wasif, *J.*, 1956, 607.
[5] Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, p. 47.
[6] Oddo and Casalino, *Gazzetta*, 1917, **47**, II, 200.
[7] Bass, Gillespie, and Robinson, *J.*, 1960, 821.

XUM

Phthalic Acid and Anhydride.—Expt. 1 confirms the results of Hantzsch [2] and of Oddo and Casalino,[6] but not those of Hammett,[5] and it appears that, in anhydrous sulphuric acid, phthalic acid accepts rather more than one proton per molecule. The first additions of phthalic anhydride to aqueous sulphuric acid (Expt. 2) give *i*-values about 1·8 units

TABLE 1. *Cryoscopic results.*

Expt.	Molality of H_2O	Molality of Phthalic acid	F. p.	*i*-Value
1.	—	—	10·359°	—
		0·0245	10·118	—
		0·0567	9·710	2·11
		0·1061	9·029	2·30
		0·1612	8·256	2·34
		Succinic acid		
3.	—	—	10·362	—
		0·0647	9·548	—
		0·1000	9·038	2·41
		0·1508	8·308	2·39
	$KHSO_4$			
7.	0·168	—	8·446	—
		0·0156	8·329	1·25
		0·0375	8·137	1·46
		0·0705	7·837	1·51
		0·1078	7·499	1·51
	H_2O	Glutaric anhydride		
8.	0·064	—	9·821	—
		0·0173	9·725	0·93
		0·0512	9·511	1·05
9.	—	—	10·358	—
		0·0225	10·109	—
		0·0613	9·522	2·55
		0·0945	9·014	2·55
		Maleic acid	—	
10.	0·180	—	8·534	—
		0·0514	7·863	2·18
		0·1052	7·147	2·22

Expt.	Molality of H_2O	Molality of Phthalic anhydride	F. p.	*i*-Value
2.	0·0851	—	9·591°	—
		0·0245	9·544	0·32
		0·0559	9·445	0·56
		0·1080	9·194	0·77
		0·1735	8·766	1·09
		Succinic anhydride		
4.	0·1473	—	8·902	—
		0·0613	8·688	0·58
		0·1044	8·531	0·61
		0·1473	8·338	0·75
5.	—	—	10·365	—
		0·0210	10·137	—
		0·0300	10·031	1·96
		0·0408	9·913	1·82
		0·0516	9·805	1·67
		0·0824	9·487	1·72
6.	—	—	10·364	—
		0·0908	9·422	—
		0·1667	8·704	1·58
		0·2467	8·009	1·45
		Maleic anhydride		
		0·1010	6·855	0·48
		0·1871	6·519	0·65
11.	0·066	—	9·799	—
		0·1010	9·389	0·68
		0·2031	8·787	0·99
		0·3489	7·865	1·05
		0·4860	6·974	1·08
		Maleic acid		
		0·0630	6·142	2·20

Expt.	Molality of $KHSO_4$	Molality of KHS_2O_7	Molality of Phthalic acid *	F. p.	*i*-Value
12.	0·074	0·206	—	7·373°	—
			0·0476	7·066	1·07
			Benzoic acid		
			0·0447	6·561	1·88
			Phthalic acid		
			0·0413	6·249	1·26
			Maleic acid		
14.	0·133	0·250	—	6·312	—
			0·0334	6·092	1·10
			0·0433	5·811	1·08

Expt.	Molality of $KHSO_4$	Molality of KHS_2O_7	Molality of Succinic acid *	F. p.	*i*-Value
13.	0·075	0·145	—	7·998°	—
			0·0261	7·774	1·43
			Water		
			0·0233	7·770	0·03
			Succinic acid		
			0·0207	7·570	1·61
			Glutaric acid		
			0·0183	7·291	2·54
			Water		
			0·0233	7·272	0·14

* Molalities in this column are those for each separate addition. All other molalities in the Table are total values.

lower than those of phthalic acid: the obvious interpretation is that the anhydride forms phthalic acidium ions by removing water, whose *i*-value is about 1·8 in these concentrations,[8] from the solvent. When the total molality of anhydride exceeds the initial molality of water in the solvent, the *i*-value for a further addition should be similar to that for an addition of the anhydride to anhydrous sulphuric acid. This is so, for the final *i*-value in Expt. 2 is 1·09, and Flowers, Gillespie, and Wasif [4] found that phthalic anhydride gives 1·14—1·18 particles per molecule in anhydrous sulphuric acid containing potassium hydrogen sulphate to repress the self-dissociation. We shall next consider Expt. 12.

Disulphuric acid in sulphuric acid behaves as a weak acid, which can be titrated with a strong base such as a metal hydrogen sulphate: [8]

$$H_2S_2O_7 + HSO_4^- \longrightarrow HS_2O_7^- + H_2SO_4$$

Suppose that to a sulphuric acid solution containing $HS_2O_7^-$ and HSO_4^- in comparable amounts some phthalic acid is added. If the acidium ion is formed, as in anhydrous sulphuric acid, a similar *i*-value (of about 2·3) would be found. If however the anhydride is formed the water produced will merely convert some of the hydrogen disulphate into hydrogen sulphate, with little change in freezing point (see Expt. 13): the observed freezing-point depression will be due almost entirely to phthalic anhydride. In fact the average *i*-value for two additions is 1·16, in good agreement with the results of Gillespie and his co-workers for phthalic anhydride in anhydrous sulphuric acid containing potassium hydrogen sulphate. (An addition of benzoic acid has been made in Expt. 12 to show that a simple base [2,6] gives the expected two-fold freezing-point depression in this solvent mixture [1]).

It has now been shown that, in sulphuric acid containing a small excess of water, phthalic anhydride is converted into phthalic acidium, whilst in solutions containing a small excess of sulphur trioxide phthalic acid is converted into the anhydride. Evidently the different behaviour in 100% sulphuric acid of phthalic acid and phthalic anhydride is not due to a kinetic impediment to their interconversion. The equilibrium (1) must be balanced in the region of 100% sulphuric acid.

The freezing-point depression for phthalic anhydride is 10—15% higher than that expected for a non-electrolyte.[4,9] This can be explained either by a small degree of protonation, or by a fractional conversion into phthalic acidium. These two possibilities are distinguished by Expt. 12, for the hydrogen disulphate should reduce any tendency to form acidium ions that phthalic anhydride might have in the less water-deficient solvent used by Gillespie and his co-workers. The similarity of the cryoscopic results suggests that phthalic anhydride ionises as a base in each solution to a similar extent. This is reasonable since, by the equilibrium $B + H_2SO_4 \rightleftharpoons HB^+ + HSO_4^-$ where B is any base, the acidity of concentrated sulphuric acid solutions is determined only by the concentration of bisulphate ion, which is approximately the same in the two solutions.

Succinic Acid and Anhydride.—In both aqueous sulphuric acid [10] and anhydrous acid (Expt. 3) succinic acid appears to accept about 1·5 protons per molecule. In the aqueous solvent (Expt. 4) succinic anhydride has an *i*-value about 1·8 units less than that of succinic acid, and it seems clear that water is removed from the solvent as in the case of phthalic anhydride. The behaviour of the anhydride in 100% sulphuric acid is less simple (Expt 5 and 6). The observed *i*-values vary from 1·96 to 1·45. High *i*-values and a high rate of change of the *i*-value with total molality are obtained for small additions; and lower *i*-values, and a low rate of change, for larger additions. Evidently some equilibrium, either equilibrium (1) or the acid–base equilibrium, is being suppressed by increasing the anhydride concentration. The change of *i*-value with molality must be due to a shift

[8] Gillespie, *J.*, 1950, 1493.
[9] Brayford and Wyatt, *J.*, 1955, 3453.
[10] Wiles, *J.*, 1953, 996.

XUM

in the acid–base equilibrium, since the effect is not observed (Expt. 7) in anhydrous acid containing a moderate concentration of bisulphate ion (added as the potassium salt), which has a lowering and buffering effect on the acidity but does not appreciably alter the water affinity. In this solution *i*-values of about 1·5 are obtained even for small additions, and, as with the phthalic system, similar *i*-values are found in sulphuric acid containing potassium hydrogen disulphate and potassium hydrogen sulphate. The results are consistent with these conclusions: that succinic anhydride does not form acidium ions in 100% sulphuric acid; that in the presence of a moderate concentration of bisulphate ion the anhydride is about half ionised as a base; and that succinic acid forms the anhydride in solutions containing excess of sulphur trioxide. The position of equilibrium (1) is similar to that in the phthalic system.

Glutaric Acid and Anhydride.—Wiles [10] gives the *i*-value of glutaric acid in aqueous sulphuric acid as 2·6. Similar values are found for the anhydride in 100% sulphuric acid (Expt. 9), and for glutaric acid in sulphuric acid containing potassium hydrogen disulphate and potassium hydrogen sulphate (Expt. 13). The *i*-values for the anhydride in aqueous acid are about 1·7 units lower (Expt. 8). The results are explained by assuming that glutaric acid accepts about 1·6 protons per molecule, and that the anhydride forms the acidium ion under all the conditions tried. (An alternative interpretation, that the anhydride exists as a polyacid base in the water-deficient solvents is rejected because phthalic and succinic anhydrides are only weak monoacid bases.)

Maleic Acid and Anhydride.—The results obtained in experiments 10, 11, and 14, are almost indistinguishable from the results for phthalic acid and anhydride. The interpretation is the same.

Some Useful Cryoscopic Mixtures.—Cryoscopic measurements in pure or aqueous sulphuric acid are seldom sufficient to establish the behaviour of a solute, as the present examples suggest. The reason for this is that acid–base reactions, and reactions which take water from the solvent (as in various types of solvolysis) or produce water (as in sulphation and sulphonation), are common in sulphuric acid, and they often occur together. Abstraction of water by anhydrides is a specific problem of this kind, and it is evident that some of the conclusions would not have been reached without the use of the solvent mixture H_2SO_4–KHS_2O_7–$KHSO_4$.

The characteristics of this and three other solvent mixtures are summarised in Table 2.

TABLE 2. *Some useful cryoscopic mixtures.*

Essential constituents (in addition) to H_2SO_4)	Acidity (relative to pure sulphuric acid)	Water affinity	Change in *i*-value associated with: * transfer of a proton to the solute	extraction of a water molecule from the solute	addition of a water molecule to the solute
$HS_2O_7^-$, HSO_4^- ...	less	greater	+1	0	0
$H_2S_2O_7$, $HS_2O_7^-$ ...	greater	greater	0	−1	+1
$H_3SO_4^+$ †	greater	similar	−1	0	+1
$H_3SO_4^+$,† H_3O^+ ...	greater	less	−1	0	0

* The contribution from the solute species is excluded. Thus, *e.g.*, to determine the *i*-value for a solute to which a proton is added and from which a water molecule is extracted, add the values appropriate to the solvent mixture in the fourth and fifth columns; and add 1 for the solute fragment.

† Produced by the reaction $H_3BO_3 + 3SO_3 + 2H_2SO_4 \longrightarrow H_3SO_4^+ + B(HSO_4)_4^-$ (see reference 11).

Gillespie's fundamental work on the cryoscopy of sulphuric acid is the basis of all four solvent mixtures, but the application of this knowledge to the examination of solutes appears to be new. The first mixture has been successfully used in studying the behaviour of certain phenols in sulphuric acid,[12] and the third and fourth have been of value in a

[11] Flowers, Gillespie, and Oubridge, *J.*, 1956, 1925.
[12] Leisten, unpublished experiments.

XUM

study of nitriles.[13] The second has not yet been used. (It could be applied in the present problem to prove that glutaric anhydride does not exist as a polyacid base, a possibility that was rejected in an earlier section by analogy alone.) An examination of Table 2 will suggest that the four solutions are complementary. Together they form a versatile and powerful addition to the cryoscopic method. The solutions also have potentialities in the field of reaction mechanisms.

The Anhydride–Acidium Ion Equilibrium.—The conclusion that the six-membered ring has a greater tendency to split in sulphuric acid than the five-membered ring is not unexpected: but no explanation is offered for the fact that succinic anhydride is a stronger base than phthalic and maleic anhydrides, although it is probably significant that in the last two the carbonyl groups are conjugated. One aspect of the results requires comment. The constitution of sulphuric acid has had much recent attention and in matters of detail is still under discussion.[7,14] Sulphuric acid gives rise to a number of dissociation products, of which the hydroxonium ion is certainly one, and any method of determining the concentration of the hydroxonium ion in sulphuric acid and sulphuric acid solutions that is independent of theories of self-dissociation has potential value for the study of this system. Now in the case of phthalic, succinic, and maleic anhydride, it has been shown that the ratio [acidium ion]/[anhydride] changes sharply in the region of 100% sulphuric acid. From the equilibrium (1) this ratio must be proportional to the hydroxonium-ion concentration:

$$[H_3O^+] = K \frac{[\text{acidium ion}]}{[\text{anhydride}]}$$

By measuring the ratio of acidium ion to anhydride concentration we can in principle determine the variation of the hydroxonium-ion concentration in the important region around 100% sulphuric acid.

It was considered unprofitable to use the cryoscopic results for this purpose. One reason is that the necessary computations require a knowledge of the position of equilibrium (1), which was the very problem under investigation. Fortunately phthalic anhydride in sulphuric acid absorbs at longer wavelengths in the near ultraviolet region than does the phthalic acidium ion. This gives the prospect of a method of analysis which is independent of the concentrations of other species and of the values of self-dissociation constants, and which has the further advantage that the anhydride can be used in indicator concentrations. Further work is in progress.

Experimental.—The materials were carefully purified and melted sharply. The cryoscopic method has been previously described.[15]

The writer thanks Mr. J. R. Brayford and Mr. M. C. W. Cottrill for carrying out the experiments 1 and 2, and 8 and 9, respectively.

THE UNIVERSITY, SHEFFIELD, 10. [*Received, November 18th,* 1960.]

[13] Leisten and Wright, unpublished experiments.
[14] Wyatt, *Trans. Faraday Soc.*, in the press.
[15] Leisten, *J.*, 1956, 1572.

XUM

417. *Boron Hydride Derivatives. Part VII.* The Characterisation of Some Decaborane Derivatives of the Type,* $B_{10}H_{12},2M$.

By R. J. Pace, J. Williams, and R. L. Williams.

Several derivatives of decaborane of the type $B_{10}H_{12},2M$, where M is an electron-donor, have been prepared. Their infrared spectra and ^{11}B nuclear magnetic resonance spectra have been measured to decide whether they have the structural formula $B_{10}H_{12},2M$ or $[B_{10}H_{10}]^{2-}[MH]_2^+$. Reactions involving displacement of M by a second electron-donor have been studied.

Since Schaeffer's discovery [1] of the reaction of acetonitrile with decaborane to yield bisacetonitriledecaborane, $B_{10}H_{12},2MeCN$, several other compounds of this type have been reported. They include derivatives from diethylcyanamide,[2] triphenylphosphine,[2] 2-isopropyl- and 5-2′-chloroethyl-2-methyl-tetrazole,[3] and triethylamine.[4,5] The last-named substance was shown by Hawthorne and Pitochelli [4,5] to give rise to two isomers, namely, an ionic derivative, $[B_{10}H_{10}]^{2-}[Et_3NH]_2^+$, and a covalent compound $B_{10}H_{12},2Et_3N$. We have measured the infrared and ^{11}B nuclear magnetic resonance spectra of a number of these substances to decide whether they have ionic or covalent structures.

Experimental

Compounds Studied.—Decaborane, purchased from the American Potash and Chemical Corporation, was recrystallised from hexane before use.

Bisacetonitriledecaborane. This was prepared by Schaeffer's method [1] from dry acetonitrile and decaborane and recrystallised from acetonitrile (Found: C, 22·9; H, 9·2; N, 13·8. Calc. for $C_4H_{16}B_{10}N_2$: C, 23·7; H, 9·0; N, 13·8%).

Bis(diethylcyanamide)decaborane and bis(triphenylphosphine)decaborane. These were prepared from decaborane and diethylcyanamide or triphenylphosphine by the methods of Hawthorne and Miller.[2] The diethylcyanamide compound was recrystallised from methylene chloride; the triphenylphosphine derivative was precipitated from chloroform by ether.

Bistriethylaminedecaboranes. These were prepared from bisacetonitriledecaborane and triethylamine in boiling benzene.[4] The hot benzene solution was filtered and the insoluble residue extracted with further quantities of hot benzene, which were added to the original filtrate, and the whole was concentrated. The covalent bistriethylaminedecaborane separated on cooling (Found: C, 44·3, 43·8; H, 11·6, 11·5; N, 9·6. Calc. for $C_{12}H_{42}B_{10}N_2$: C, 44·7; H, 13·1; N, 8·7%). The traces of benzene were removed from the insoluble ionic compound *in vacuo* (Found: C, 44·1; H, 12·9; N, 9·2%).

Bis(dimethyl sulphide)decaborane. The substance was prepared by refluxing decaborane (0·24 g., 0·02 mole) with dimethyl sulphide (0·30 g., 0·05 mole) in dry ether for 4 hr. The solution deposited colourless crystals of the *complex* overnight. These were filtered off, washed with ether, and dried *in vacuo*, and had m. p. 110° (decomp.) (Found: C, 19·4; H, 9·5. $C_4H_{24}B_{10}S_2$ requires C, 19·6; H, 9·9%).

Bispyridinedecaborane. Pyridine (0·17 g., 0·022 mole) in a small quantity of dry benzene was added to decaborane (0·12 g., 0·01 mole) in benzene, giving a yellow-red sticky precipitate. The whole was refluxed for 2 hr., then cooled. Hydrogen (20 ml.) was evolved (0·01 mole requires 22·4 ml.). The *product* was filtered off and on recrystallisation from hot dimethylformamide formed yellow crystals, m. p. 300° (decomp.) (Found: C, 43·0; H, 7·8; N, 10·0. $C_{10}H_{22}B_{10}N_2$ requires C, 43·1; H, 8·0; N, 10·1%).

Bis(dimethylformamide)decaborane. To decaborane (0·25 g., 0·02 mole) in benzene (5 ml.) dimethylformamide (0·30 g., 0·041 mole) was added. A suspension was formed after a few minutes' heating. The mixture was refluxed for 1 hr., 51·5 ml. of hydrogen being evolved

* Part VI, Dunstan, Blay, and R. L. Williams, *J.*, 1960, 5016.

[1] Schaeffer, *J. Amer. Chem. Soc.*, 1957, **79**, 1006.
[2] Hawthorne and Pitochelli, *J. Amer. Chem. Soc.*, 1958, **80**, 6685.
[3] Fetter, *Chem. and Ind.*, 1959, 1548.
[4] Hawthorne and Pitochelli, *J. Amer. Chem. Soc.*, 1959, **81**, 5519.
[5] Lipscomb, Hawthorne, and Pitochelli, *J. Amer. Chem. Soc.*, 1959, **81**, 5834.

XUM

(0·02 mole requires 46·5m l.). After cooling, the suspension was filtered off, washed with benzene, then ether, and dried *in vacuo*. Dissolution in dimethylformamide, followed by precipitation with ether, did not alter the infrared spectrum of the *product* which had m. p. 162° (decomp.) (Found: C, 26·7; H, 10·4; N, 11·7. $C_6H_{26}B_{10}O_2N_2$ requires C, 27·0; H, 9·8; N, 10·5%).

Bis(dimethylacetamide)decaborane. To decaborane (0·26 g., 0·21 mole) in benzene (5 ml.), dimethylacetamide (0·36 g., 0·41 mole) was added. The solution was heated. Gas evolution was rapid and two layers were formed. On cooling, the lower layer formed pale orange crystals of the *product*, m. p. 139° (decomp.) (Found: C, 31·4; H, 10·3; N, 9·8. $C_8H_{30}B_{10}O_2N_2$ requires C, 32·6; H, 10·3; N, 9·5%).

Bis-(2-bromopyridine)decaborane. This *compound* was prepared by a similar method to bispyridinedecaborane (Found: C, 27·9; H, 4·8; N, 5·0. $C_{10}H_{20}B_{10}Br_2N_2$ requires C, 27·5; H, 4·6; N, 6·4%).

Spectra.—The infrared spectra of the compounds were measured for Nujol and Fluorube mulls on a Grubb–Parsons GS2 double-beam grating spectrometer with a 2400 line/inch N.P.L. replica grating. The spectra of the corresponding donor substances were also measured as mulls, except for triphenylphosphine (solutions in CCl_4 and CS_2).

Me_2S. 2986m, 2965m, 2915s, 2854m, 2833m, 1716w, 1431vs, 1308s, 1027s, 971ms, 903w, 740w, 690m.

$(Me_2S)_2,B_{10}H_{12}$. 3025sh, 3015m, 2996w, 2923mw, 2527sh, 2504vs, 2493sh, 2457m, 1432mw, 1423s, 1412ms, 1328m, 1307w, 1086m, 1074sh, 1038m, 998vs, 976m, 965mw, 951mw, 936sh, 929m, 815vw, 795mw, 785sh, 761mw, 758mw, 678w, 643m.

MeCN. 3202w, 3164m, 3002ms, 2945ms, 2294mw, 2253s, 1715vw, 1439vs, 1414sh, 1374vs, 1224vw, 1039s, 918ms, 749m.

$(MeCN)_2,B_{10}H_{12}$. 2981sh, 2974m, 2911mw, 2536sh, 2521vs, 2480m, 2328w, 1460m, 1404s, 1359w, 1353m, 1195w, 1124sh, 1119m, 1109sh, 1078mw, 1030m, 1017sh, 1002sh, 996s, 972m, 952sh, 948mw, 939mw, 930mw, 874w, 792ms, 777m, 747m, 680sh, 674m.

$Et_2N{\cdot}CN$. 2980s, 2937m, 2880m, 2209vs, 1478sh, 1460sh, 1452s, 1400sh, 1383s, 1357m, 1325m, 1303mw, 1229s, 1179s, 1113sh, 1083s, 1071sh, 977w, 929w, 811sh, 796m, 713m.

$(Et_2N{\cdot}CN)_2,B_{10}H_{12}$. 2976ms, 2936m, 2902mw, 2874w, 2534sh, 2511vs, 2492sh, 2479sh, 2461sh, 2302s, 1493m, 1384m, 1345w, 1304s, 1272sh, 1147sh, 1120m, 1110m, 1070mw, 1009sh, 994s, 970mw, 948w, 939w, 932w, 917w, 821m, 811sh, 789mw, 777w, 730mw, 717w, 704w.

$HCO{\cdot}NMe_2$. 3072w, 2991sh, 2927m, 2856m, 2805sh, 2772w, 1674vs, 1500m, 1458sh, 1438m, 1404sh, 1396s, 1257m, 1151w, 1092s, 1063m, 865w.

$(HCO{\cdot}NMe_2)_2,B_{10}H_{12}$. 3086w, 2986w, 2930w, 2861vw, 2820w, 2760w, 2523sh, 2503vs, 2473ms, 1672vs, 1484w, 1438w, 1428m, 1416sh, 1346s, 1248mw, 1138m, 1116mw, 1080w, 1060w, 1003ms, 992sh, 980sh, 909ms, 818ms, 792m, 751w, 723w.

$AcNMe_2$. 3014w, 2930mw, 2872sh, 1643vs (CCl_4 soln. 1658), 1548w, 1499m, 1445mw, 1412ms, 1395s, 1356w, 1265w, 1188mw, 1177sh, 1060w, 1035w, 1012m.

$(AcNMe_2)_2,B_{10}H_{12}$. 3035vw, 2975vw, 2939w, 2873vw, 2856vw, 2522sh, 2494vs, 2451sh, 1618vs, 1495ms, 1431m, 1402ms, 1367w, 1260m, 1133m, 1120m, 1025w, 1011w, 988s, 969m, 890m, 819s, 735w, 721w, 674ms.

Et_3N. 2970vs, 2933s, 2895mw, 2874m, 2797s, 2753sh, 2721sh, 2709sh, 1468m, 1449m, 1382s, 1371sh, 1357w, 1345w, 1334sh, 1309sh, 1293m, 1268sh, 1211sh, 1204s, 1145w, 1136w, 1094sh, 1085m, 1070s, 1058sh, 1047sh, 1019w, 998w, 919w, 901w, 800w, 781w, 743m, 736m.

$(Et_3N)_2,B_{10}H_{12}$. 3009m, 3000m, 2987ms, 2967m, 2940m, 2885sh, 2821w, 2526s, 2502vs, 2490s, 2477ms, 1467s, 1438m, 1415w, 1390m, 1382s, 1365w, 1354w, 1343w, 1315vw, 1285vw, 1214m, 1192w, 1177vw, 1165w, 1147m, 1113vw, 1094w, 1082vw, 1068w, 1057vw, 1018s, 1010sh, 962w, 955w, 933vw, 910sh, 901mw, 893w, 833w, 813w, 780ms, 767ms, 753vw, 743w, 669w.

$(Et_3NH)^+_2PtCl_6^{2-}$. 3085vs, 3008sh, 3003w, 2986w, 2979w, 2944vw, 2886vw, 2821vw, 2755vw, 1480w, 1468s, 1455ms, 1446m, 1431w, 1415m, 1396sh, 1391ms, 1388sh, 1360w, 1341vw, 1315vw, 1305vw, 1286w, 1268w, 1179sh, 1172w, 1162ms, 1091vw, 1064m, 1045w, 1012ms, 897w, 894sh 840m, 805mw, 775w, 729mw.

$(Et_3NH)^+_2,B_{10}H_{10}^{2-}$. 3060s, 3015w, 2979w, 2955w, 2889vw, 2848vw, 2776vw, 2753vw, 2664vw, 2536m, 2494sh, 2465vs, 2447sh, 2410sh, 2353m, 1679w, 1614w, 1459ms, 1448s, 1405ms, 1362w, 1162m, 1076w, 1060w, 1034s, 1014sh, 928w, 894w, 844m, 792m, 777sh, 726w.

Ph_3P. 3139w, 3070s, 3054s, 3030m, 3014m, 3000m, 2910vw, 1965sh, 1952w, 1891sh,

XUM

1881w, 1824sh, 1812w, 1773sh, 1758w, 1656w, 1585m, 1571sh, 1480s, 1433s, 1378w, 1325m, 1305m, 1278w, 1201w, 1181m, 1157w, 1119w, 1088ms, 1069m, 1027s, 999m, 984sh, 966vw, 914w, 846w, 741vs, 719w, 699sh, 693vs.

$(Ph_3P)_2,B_{10}H_{12}$. 3073sh, 3057w, 3022vw, 3005vw, 2950vw, 2924vw, 2859vw, 2540sh, 2519vs, 2472sh, 2431sh, 1973vw, 1901vw, 1814vw, 1746vw, 1668vw, 1588w, 1573w, 1482s, 1436s, 1343w, 1312w, 1186m, 1160m, 1120sh, 1101s, 1070m, 1062m, 1028m, 999m, 978m, 945m, 939sh, 925sh, 915m, 889mw, 847vw, 819vw, 801mw, 755sh, 743s, 722sh, 711s, 693vs.

$2\text{-}Br\cdot C_5H_4N$. 3130w, 3081sh, 3068sh, 3051s, 2990m, 2890w, 1602w, 1571s, 1560s, 1459sh, 1448s, 1414s, 1351w, 1282mw, 1239w, 1148m, 1117sh, 1106s, 1091w, 1077s, 1042ms, 1014w, 1003w, 987ms, 759vs, 724w, 700s.

$(Br\cdot C_5H_4N)_2,B_{10}H_{12}$. 3111vw, 3090vw, 3073vw, 3059vw, 3009vw, 2933vw, 2583m, 2570m, 2522sh, 2502vs, 2475ms, 1601m, 1554mw, 1509w, 1459s, 1425s, 1354vw, 1344vw, 1285m, 1225vw, 1170w, 1149w, 1118w, 1094m, 1083sh, 1071ms, 1048mw, 1011sh, 998s, 977m, 957w, 938sh, 933mw, 922w, 902w, 881vw, 858vw, 809vw, 791m, 784sh, 770s, 758sh, 730sh, 720m.

C_5H_5N. 3146vw, 3079m, 3053mw, 3032sh, 3026m, 3001mw, 2989sh, 2955w, 2932vw, 2910vw, 1989w, 1948sh, 1924w, 1873w, 1685vw, 1634w, 1599m, 1583sh, 1574sh, 1483m, 1438s, 1377w, 1356w, 1293vw, 1218m, 1147m, 1069m, 1031ms, 991ms, 940vw, 883vw, 747sh, 703vs.

$(C_5H_5N)_2,B_{10}H_{12}$. 3122sh, 3114sh, 3104vw, 3083sh, 3072vw, 3062sh, 3038vw, 2525sh, 2509vs, 2481s, 2461m, 1670w, 1623mw, 1614sh, 1574w, 1485m, 1458s, 1417w, 1354w, 1344mw, 1314vw, 1254mw, 1209m, 1162w, 1157sh, 1132m, 1121ms, 1095m, 1080sh, 1075m, 1058m, 1023sh, 1013sh, 999vs, 980m, 976m, 964vw, 955w, 941sh, 938m, 925sh, 903sh, 888vw, 871w, 867mw, 794m, 779s, 772ms, 759m, 747mw, 732w, 709m, 687vs.

$B_{10}H_{14}$. 2625sh, 2613ms, 2592sh, 2586vs, 2571vs, 2548sh, 2538s, 1970w, 1934mw, 1892m, 1557ms, 1514vs, 1467ms, 1103m, 1037m, 1007s, 971ms, 965ms, 959sh, 941sh, 938ms, 924sh, 921s, 902s, 862sh, 859s, 821sh, 814s, 774sh, 766s, 757w, 747m, 723vs, 709w, 700w, 693vw, 668vw 649w, 611ms.

^{11}B nuclear magnetic resonance spectra were measured at 12 Mc./sec. with a Varian Associates V 4310 high-resolution spectrometer. Dimethylformamide was used as solvent for the compounds except that the dimethyl sulphide derivative was in methylene chloride, and the acetonitrile and dimethylacetamide compounds were in acetonitrile. After measurement, the solutes were recovered from solution by evaporation of the solvent or by precipitation with ether. Their infrared spectra showed that no reaction had taken place.

Displacement Reactions.—Some displacement reactions, $B_{10}H_{12}M_2 + 2M' \longrightarrow B_{10}H_{12}M'_2 + 2M$, were studied.

(*a*) The original boron compound, identified by its infrared spectrum, was recovered after the following pairs had been heated together: bisdimethylformamidedecaborane–dimethyl sulphide, –acetonitrile, or –triethylamine (no solvent); bisdimethylacetamidedecaborane–dimethylformamide; bistriethylaminedecaborane(covalent)–pyridine; bispyridinedecaborane–triethyamine or –triphenylphosphine in dimethylformamide; bistriphenylphosphine–pyridine in dimethylformamide.

(*b*) Bis(dimethyl sulphide)decaborane was boiled in acetonitrile for a few minutes and the solvent removed. The infrared spectrum of the residue was identical with that of bisacetonitriledecaborane.

(*c*) Bisdimethylformamidedecaborane was heated with triethylamine in dimethylformamide, and the solute precipitated by ether. The infrared spectrum of the product showed it to be a mixture of the ionic and the covalent form of bistriethylaminedecaborane.

(*d*) Bisdimethylformamidedecaborane was heated in pyridine. On cooling, bispyridinedecaborane separated, its identity being confirmed by the spectrum.

Attempts to make a bisdimethylnitrosaminedecaborane by direct reaction of dimethylnitrosamine with decaborane in benzene or by displacement from bis(dimethyl sulphide)decaborane or bisacetonitriledecaborane caused decomposition to hydroxylated compounds.

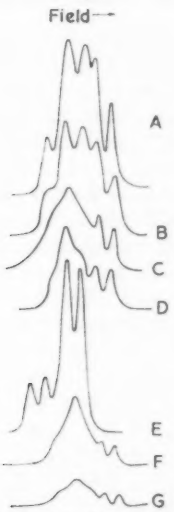
Discussion

Nuclear Magnetic Resonance Spectra.—Hawthorne *et al.*[4,5] converted the ionic bistriethylaminedecaborane $[Et_3NH]^+_2[B_{10}H_{10}]^{2-}$ into a tetramethylammonium salt and showed that the ^{11}B nuclear magnetic spectrum of this substance consisted of a low-field doublet of strength 1 and a high-field doublet of strength 4. The spectrum of the ionic bistriethyl-

amine compound (Fig. 1) is identical with this and differs considerably from those of the other decaborane derivatives. The other derivatives therefore have covalently bonded structures in which the ligands donate electrons to the $B_{10}H_{12}$ unit.

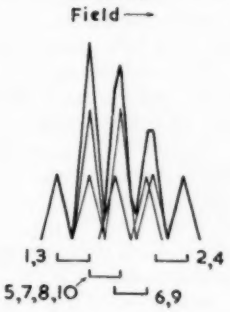
The structure of bisacetonitriledecaborane has been shown by Reddy and Lipscomb [6,7] to have the acetonitrile units attached at the 6,9-positions and to have positions 5 and 7 linked by bridge protons to positions 10 and 8, respectively (cf. I; the Y bonds represent

FIG. 1.

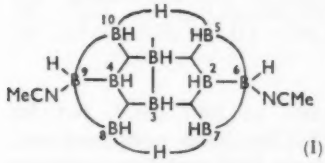


The ^{11}B *nuclear magnetic resonance spectra of*:
(A) $(Me_2S)_2B_{10}H_{12}$; (B) $(MeCN)_2B_{10}H_{12}$; (C) $(HCO{\cdot}NMe_2)_2B_{10}H_{12}$; (D) $(AcNMe_2)_2B_{10}H_{12}$; (E) $(Et_2NH)_2B_{10}H_{10}$; (F) $(Et_3N)_2B_{10}H_{12}$; (G) $(C_5H_5N)_2B_{10}H_{12}$.

FIG. 2. *Theoretical spectrum for* $M_2B_{10}H_{12}$.



three-centre bond approximations; there is, of course, no carbon atom at these junctions). The dispositions of the boron atoms are at the corners of two pentagonal pyramids sharing a common edge, as in decaborane. Accordingly, the ^{11}B nuclear magnetic resonance spectrum will be made up of a number of doublets similar to those of decaborane.[8] If the major changes in charge on going from decaborane to the bis-derivative are restricted to an increase in electron density at the 6,9-positions, it would be expected that the 2,4-doublet would lie on the high-field side of the spectrum, the 5,7,8,10-doublet at a centre-field position, and the 1,3-doublet at low field, as with decaborane. The 6,9-doublet would be expected to shift towards higher field as in shifts observed for this doublet in decaboranes methylated at the 1-, 2-, 3-, and 4-positions.[9] A theoretical spectrum based on these assumptions (Fig. 2) shows satisfactory agreement with those observed, especially with the bis(dimethyl sulphide) and the bisacetonitrile compound.



(I)

Infrared Spectra.—The spectra of the bis-derivatives of decaborane, $B_{10}H_{12}{,}2M$, together with those of the ligands, M, are shown in Fig. 3. Each spectrum falls into two

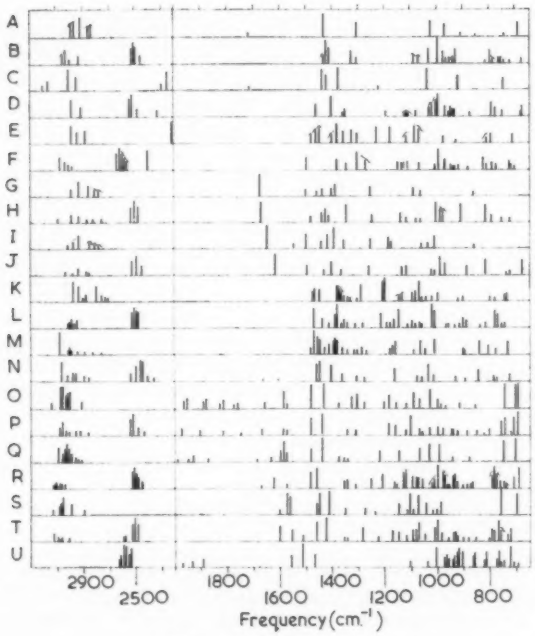
[6] Reddy and Lipscomb, *J. Amer. Chem. Soc.*, 1959, **81**, 754.
[7] Reddy and Lipscomb, *J. Chem. Phys.*, 1959, **31**, 610.
[8] R. E. Williams and Shapiro, *J. Chem. Phys.*, 1958, **29**, 677.
[9] R. L. Williams, Dunstan, and Blay, *J.*, 1960, 5006.

XUM

parts, that due to vibrations of the $B_{10}H_{12}$ unit, which is common to all the spectra, and that of the electron-donating unit, M. Thus all the spectra have a number of strong absorptions in the range 2520—2490 cm.$^{-1}$, due to the terminal B–H stretching vibrations, which are replaced by single peaks when solutions are measured. Decaborane behaves similarly, but its band centre lies at 2580 cm.$^{-1}$. The $[B_{10}H_{10}]^{2-}$ ion in the triethylammonium salt has its band centre at the much lower frequency of 2450 cm.$^{-1}$.

Apart from absorption of variable intensity near 930—900 cm.$^{-1}$, the only strong band common to all the spectra lies in the range 1015—990 cm.$^{-1}$, often with a weaker satellite of

FIG. 3.



The infrared spectra of:

(A) Me_2S; (B) $(Me_2S)_2,B_{10}H_{12}$; (C) MeCN; (D) $(MeCN)_2,B_{10}H_{12}$; (E) $Et_2N{\cdot}CN$; (F) $[Et_2N{\cdot}CN)_2,B_{10}H_{12}$; (G) $HCO{\cdot}NMe_2$; (H) $(HCO{\cdot}NMe_2)_2,B_{10}H_{12}$; (I) $AcNMe_2$; (J) $(AcNMe_2)_2,B_{10}H_{12}$; (K) Et_3N; (L) $(Et_3N)_2,B_{10}H_{12}$; (M) $(Et_3NH)^+_2PtCl_6^{2-}$; (N) $(Et_3NH)_2,B_{10}H_{10}$; (O) Ph_3P; (P) $(Ph_3P)_2,B_{10}H_{12}$; (Q) C_5H_5N; (R) $(C_5H_5N)_2,B_{10}H_{12}$; (S) 2-BrC_5H_4N; (T) $(BrC_5H_4N)_2,B_{10}H_{12}$; (U) $B_{10}H_{14}$.

lower frequency. This band also occurs for decaborane, at 1007 cm.$^{-1}$, but for $[Et_3NH]^+_2[B_{10}H_{10}]^{2-}$ its position has risen to 1034 cm.$^{-1}$. The latter compound can, therefore, be distinguished from the $B_{10}H_{12},2M$ type by its lower B–H stretching frequency and the raised value of the band near 1000 cm.$^{-1}$.

The 1000 cm.$^{-1}$ band can be assigned to a terminal B–H deformation vibration since it persists in the spectrum of $B_{10}H_{10}D_4$, deuterated in the bridge positions by the method of Hawthorne and Miller.[10,11] On the other hand, this band is reduced in intensity in 2,4,5,7,8,10-hexadeuterodecaborane prepared by the action of deuterium chloride and

[10] Hawthorne and Miller, *J. Amer. Chem. Soc.*, 1958, **80**, 754.
[11] Miller and Hawthorne, *J. Amer. Chem. Soc.*, 1959, **81**, 4501.

aluminium chloride on decaborane [12] and has disappeared completely from the spectrum [11] of $B_{10}D_{14}$.

The strong band at 1514 cm.$^{-1}$ in the decaborane spectrum, which is an alternative possibility for the B–H deformation vibration, by analogy with Hrostowski and Pimentel's assignment [13] for pentaborane-9, can be eliminated, since this band has disappeared from the spectrum of the bridge-deuterated $B_{10}H_{10}D_4$ and has been replaced by a strong band near 1160 cm.$^{-1}$ (ratio 1·30 : 1). Moreover, the $B_{10}H_{12}$,2M compounds differ only from decaborane in their hydrogen-bridge systems, and in none of them is there a strong band near 1500 cm.$^{-1}$.

The contribution, to the spectrum, of the ligand M differs from compound to compound and also differs from the spectrum of M in its unbonded state. It is therefore not possible to make detailed analyses except where M has a simple spectrum. Thus, in the case of dimethyl sulphide, bands are observed near 2980, 2915 (antisymm. ν-CH_3) and 2840 (symm. ν-CH_3), 1431 (antisymm. δ-CH_3) and 1308 (symm. δ-CH_3), 1027 and 971 (CH_3-rock), and 690 cm.$^{-1}$ (ν-CS) [14]. On formation of the bis(dimethyl sulphide)decaborane most of these bands change slightly in frequency; *e.g.*, the antisymmetric and symmetric ν-CH_3 vibrations increase to 3015 and 2923 cm.$^{-1}$. The methyl deformation vibrations split into several components but remain largely unaltered at 1423 and 1328 cm.$^{-1}$ respectively. Similarly, the methyl rocking vibrations can be identified with the bands at 1038 and 976 cm.$^{-1}$ and the C–S stretching vibration with that at 643 cm.$^{-1}$. The slight changes in the spectrum indicate a small change only in the electronic structure of the molecule and it is not surprising, therefore, that dimethyl sulphide is the most easily displaced ligand.

With the bisacetonitrile compound, it is possible to identify the bands at 2974 (antisymm. ν-CH_3), 2911 (symm. ν-CH_3), 2328 (ν-C≡N), 1460 (antisymm. δ-CH_3), 1404 (symm. δ-CH_3), 1078 (CH_3-rock), and 948 cm.$^{-1}$ (possibly ν-C–C) with the corresponding bands in acetonitrile [15] at 3002, 2945, 2252, 1439, 1376, 1040, and 919 cm.$^{-1}$. The most significant difference is the increase of the C≡N frequency by 75 cm.$^{-1}$ on complex formation. This change parallels that noted by Gerrard *et al.*[16] on formation of complexes of the type RCN,BCl_3. Because of the relative insensitivity of the frequency of the CN group to environmental changes,[17] the shift indicates a strong interaction between the group and the $B_{10}H_{12}$ unit.

Diethylcyanamide behaves in a similar manner to acetonitrile, but a vibrational assignment is not possible, except for a few bands, because of the complexity of the spectrum. The absence of a strong band at 2800 cm.$^{-1}$ indicates that the lone pair of electrons of the diethylamino-group is delocalised [18] and this is reflected by the lower CN frequency, namely, 2209 cm.$^{-1}$ compared with 2250 cm.$^{-1}$ for normal nitriles. On formation of the decaborane complex the CN frequency rises by 93 cm.$^{-1}$ to 2302 cm.$^{-1}$, which shows that the molecule is linked through the CN group rather than the nitrogen of the diethylamino-group. The lone pair of the latter remains delocalised since there is no strong absorption near 2800 cm.$^{-1}$.

(I) (II) (III) (IV)

Gerrard *et al.*[16] explained the increase in CN frequency in their complexes by the absence of canonical form (IV) from the normal CN resonance because of its different geometry from form (III). However, it is unlikely that form (II) makes a significant contribution to

[12] Dupont and Hawthorne, *J. Amer. Chem. Soc.*, 1959, **81**, 4998.
[13] Hrostowski and Pimentel, *J. Amer. Chem. Soc.*, 1954, **76**, 998.
[14] Trotter and Thompson, *J.*, 1946, 486.
[15] Venkateswarlu, *J. Chem. Phys.*, 1951, **19**, 293.
[16] Gerrard, Lappert, Pyszora, and Wallis, *J.*, 1960, 2182.
[17] Mander and Thompson, *Trans. Faraday Soc.*, 1957, **53**, 1402.
[18] Hill and Meakins, *J.*, 1958, 760; Braunholtz, Ebsworth, Mann, and Sheppard, *J.*, 1958, 2780.

XUM

the nitrile structure, since the dipole moments of nitriles which were cited [19] as evidence for its existence can more reasonably be attributed [20] to the lone pair of electrons on the nitrogen. A comparison with the C≡C link, where no contribution from $\overset{+}{C}=\overset{-}{C}$ would be expected, confirms this: both bonds have very similar frequencies: [21] C≡C, 2260—2190 cm.$^{-1}$; C≡N, 2260—2240 cm.$^{-1}$.

Formation of the nitrile complex places a formal positive charge on the nitrogen (III). This would be expected [22] to reduce the covalent radius by about 0·02 Å, and this is confirmed on the structural analysis of the acetonitrile–boron trifluoride complex [23] (MeCN, r_{CN} 1·16 Å; $MeCN,BF_3$, r_{CN} 1·13 Å). The frequency increase corresponding to a bond-shortening of this size can be estimated from Badger's rule [24] to be approximately 150 cm.$^{-1}$, which compares with the observed shifts of 75—90 cm.$^{-1}$.

In the case of diethylcyanamide, the additional canonical form (V) makes a small contribution to the resonance structure, which is little altered in the complex. However,

$$Et_2\overset{\cdot\cdot}{N}-C\equiv N \longleftrightarrow Et_2\overset{+}{N}=C=\overset{-}{N} \text{ (V)} \qquad Et_2\overset{+}{N}=C=N\rightarrow\overset{-}{M} \text{ (VI)}$$

a contribution from structure (VI) to the complex is not possible on steric grounds and the same mechanism as for acetonitrile applies to the frequency increase.

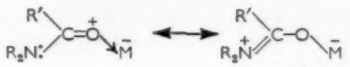
An alternative explanation, originally proposed [25] for the nitrile oxides, R·C≡N→O, is that the increase is due to coupling of the C≡N vibration with the N→M vibration. This is here very unlikely because of the wide separation of these two frequencies. Calculations for the linear system, C–N–M, on the basis that ν_{N-M} lies [26] near 700 cm.$^{-1}$, indicate a maximum increase of 30 cm.$^{-1}$ when the atomic mass of M is 11 (the frequency increase becomes smaller as the mass of M increases).

The spectrum of dimethylformamide is relatively simple and follows the pattern expected for a disubstituted amide [27] with amide I (CO) and amide III (CN) bands at 1674 and 1257 cm.$^{-1}$, and the methyl stretching, deformation, and rocking vibrations near 2900, 1450, and 1092 cm.$^{-1}$, respectively. The absence of a strong band at 2800 cm.$^{-1}$ shows that the lone pair of electrons on the nitrogen is delocalised. On formation of the bis-compound, most of the frequencies change but little, with the possible exception of the methyl rocking frequencies which rise to 1125 cm.$^{-1}$. The carbonyl frequency falls slightly to 1672 cm.$^{-1}$. Gerrard *et al.*[28] found that for nearly all of their amide complexes with boron trichloride and bromide there is a fall in the carbonyl frequency compared with that of the free amide in the liquid state or in methylene chloride solution. The two exceptions are the complexes of dimethylformamide and dimethylacetamide, which have slightly higher values. However, the carbonyl frequencies of disubstituted amides are very sensitive to solvent effects [29] and it is preferable to use the vapour or hexane-solution values for comparisons. These are 1716 and 1696 cm.$^{-1}$ for dimethylformamide and 1691 and 1675 cm.$^{-1}$ for the acetamide. On this basis, there is a considerable fall in the carbonyl frequencies both with the boron trihalide complexes and the bisdimethylformamide derivative compared with the free amide. This indicates that the carbonyl-oxygen atom is the point of attachment, since, unlike the position with the nitrile complexes, there are no geometrical objections to the contribution of form (VIII) and correspondingly no formal positive

[19] Pauling, " Nature of the Chemical Bond," Cornell Univ. Press, Ithaca, U.S.A., 1948, p. 75.
[20] Coulson, " Valence," Clarendon Press, Oxford, 1952, p. 209.
[21] Bellamy, " The Infra-red Spectra of Complex Molecules," Methuen, London, 1958, pp. 58, 263.
[22] Ref. 19, p. 169.
[23] Hoard, Owen, Buzzell, and Salmon, *Acta Cryst.*, 1950, **3**, 130.
[24] Badger, *J. Chem. Phys.*, 1934, **2**, 128.
[25] Califano, Moccia, Scarpati, and Speroni, *J. Chem. Phys.*, 1957, **26**, 1777.
[26] Taylor and Cluff, *Nature*, 1958, **182**, 390.
[27] Ref. 21, p. 205.
[28] Gerrard, Lappert, Pyszora, and Wallis, *J.*, 1960, 2144.
[29] Bellamy and R. L. Williams, *Trans. Faraday Soc.*, 1959, **55**, 14.

charge on the oxygen. Co-ordination through the dimethylamino-group, which would suppress form (VII), would be expected to raise the carbonyl frequency.

(VII)



(VIII)

The dimethylacetamide compound is similar to the formamide derivative. Most of the bands in the parent molecule appear with slight displacements in the spectrum of the bis-derivative, except for the carbonyl band, whose frequency falls to 1618 cm.$^{-1}$.

With both the dimethylformamide and the acetamide derivative, new strong bands appear in the spectrum near 890 and 819 cm.$^{-1}$. It is possible that these are associated with the boron–oxygen bond.

In the case of triethylamine, assignment is impossible because of the interactions which can take place between the various CH deformation vibrations and those due to the C–C and C–N stretching modes. However, there is a strong band at 2797 cm.$^{-1}$ in addition to the normal CH bands, which is characteristic of a lone pair of electrons on the nitrogen.[18] This band disappears from the spectrum of the covalent bistriethylaminedecaborane, confirming the formation of a co-ordinate link which is also shown by the appearance of strong bands at 1147 and 780 cm.$^{-1}$, both of which have been associated with N→B links.[30]

The spectrum of the ionic triethylamine derivative, $[Et_3NH]^+_2[B_{10}H_{10}]^{2-}$, is considerably simpler than that of the covalent compound and is characterised particularly by a strong band at 3060 cm.$^{-1}$, which can be assigned to the NH^+ stretching vibration. Hitherto, the NH^+ vibration of tertiary ammonium salts has been reported [31,32] to lie near 2740 cm.$^{-1}$ or lower, but in each case the salts are those of strong acids and the spectrum is complicated by very strong hydrogen bonding. With the chloroplatinate of triethylamine, hydrogen bonding is weaker and a strong band is found at 3085 cm.$^{-1}$. The remainder of the chloroplatinate spectrum also bears a strong similarity to that of the ionic decaborane compound, as Fig. 3 and the listed frequencies show.

The spectra of the three remaining compounds are less informative since the spectrum of each parent molecule is complex. With triphenylphosphine, the bands arise mainly from the phenyl groups, and frequency changes on complex formation will be slight because of relay through the phosphorus. This is borne out in practice. The parent and complex have similar spectra. However, it is noteworthy that the δ-BH band at 1000 cm.$^{-1}$ is abnormally weak.

The changes in the spectrum of pyridine on complex formation with boron trichloride have been fully discussed by Greenwood and Wade.[30] Similar changes take place with bispyridinedecaborane and it is possible to identify in the spectrum of the complex all the bands listed by Greenwood and Wade as due to the pyridine. These also lie at similar frequencies. In particular, the strong band at 1113 cm.$^{-1}$ associated with the formation of an N→B link is found as a strong doublet at 1121 cm.$^{-1}$ in bispyridinedecaborane.

2-Bromopyridine follows a similar pattern to pyridine. The ring stretching frequencies in the 1600—1400 cm.$^{-1}$ region are increased on complex formation, as are the out of plane CH deformations at 775—700 cm.$^{-1}$. The remainder of the spectrum is complex, but a new band appears near 1090 cm.$^{-1}$ in a similar way to those in pyridine–boron trichloride and bispyridinedecaborane.

Displacement Reactions.—The displacement reactions discussed in the Experimental section taken with those reported by Hawthorne and Pitochelli [4] make it possible to write the ligands in increasing bonding strengths, $Me_2S < MeCN < Et_2N{\cdot}CN < HCO{\cdot}NMe_2 = AcNMe_2 < Et_3N = C_5H_5N = Ph_3P$.

[30] Greenwood and Wade, *J.*, 1960, 1130.
[31] Chenon and Sandorfy, *Canad. J. Chem.*, 1958, **36**, 1181; Brissette and Sandorfy, *ibid.*, 1960, **38**, 34.
[32] Bellanato and Barcello, *Anales real Soc. espan. Fis. Quim.*, 1956, **52**, *B*, 469.

XUM

Each of these substances will displace the ligand from the complex on its left provided a solution of the latter is used.

We thank Mr. A. C. Thomas (C.D.E.E., Porton) for analysing the samples, and Mr. G. Kidd (University College, London) for his co-operation in obtaining the nuclear magnetic resonance spectra.

MINISTRY OF AVIATION, EXPLOSIVES RESEARCH AND DEVELOPMENT ESTABLISHMENT,
WALTHAM ABBEY, ESSEX. [*Received, December 7th*, 1960.]

---

418. *Polyfluoroarenes. Part III.*[1] *A New Synthesis of Hexafluorobenzene.*

By J. M. BIRCHALL, R. N. HASZELDINE, and A. R. PARKINSON.

Pyrolysis of 1-chloro-1,2-difluoroethylene over a platinum surface at 600° gave hexafluorobenzene in 14% yield. Hexafluorobenzene was not produced by pyrolysis of 1,2-dichlorodifluoroethylene under a variety of conditions, but low yields were obtained by co-pyrolysis with hydrogen.

IN Part I of this series [2] it was suggested that the formation of hexafluorobenzene during the pyrolysis of tribromofluoromethane involved difluoroacetylene as an intermediate:

$$CFBr_3 \longrightarrow CFBr_2{\cdot}CFBr_2 \longrightarrow C_2F_2 \longrightarrow C_6F_6$$

This view led to an investigation of the pyrolysis of a number of 1,2-difluoroethylenes which might, by thermal dehalogenation or dehydrohalogenation, yield difluoroacetylene and hence hexafluorobenzene. The results of studies of the pyrolysis of 1,2-dichlorodifluoroethylene and 1-chloro-1,2-difluoroethylene are now reported.

1,2-Dichlorodifluoroethylene was prepared from a mixture of tetrachlorodifluoroethanes containing 60—90% of the symmetrical isomer. This mixture could not be separated by distillation ($CF_2Cl{\cdot}CCl_3$, b. p.[3] 92·8°; $CFCl_2{\cdot}CFCl_2$, b. p.[3] 91·5°) or by gas–liquid chromatography, but dechlorination with zinc in ethanol gave the related dichlorodifluoroethylenes in excellent yield (>90%). Separation of the mixture of olefins by distillation was not attempted ($CF_2{:}CCl_2$, b. p.[4] 19°; *cis*-CFCl:CFCl, b. p.[3] 21·1°; *trans*-CFCl:CFCl, b. p.[3] 22°), but the mixture was analysed by gas–liquid chromatography and the symmetrical olefin was isolated by utilising the preferential reaction of 1,1-dichlorodifluoroethylene with ethoxide ion. The mixture of olefins was treated under mild conditions with an excess of ethanol containing a trace of sodium ethoxide. 1,1-Dichlorodifluoroethylene added ethanol and remained in solution,[5] and 1,2-dichlorodifluoroethylene was removed by distillation. The latter olefin undergoes base-catalysed addition of ethanol only under more vigorous conditions.[6]

Photochemical reaction of hydrogen bromide with 1,2-dichlorodifluoroethylene, followed by dehalogenation of the adduct, gave 1-chloro-1,2-difluoroethylene in 87% overall yield.

1-Chloro-1,2-difluoroethylene was pyrolysed by passage under atmospheric pressure through a platinum tube at 590—650° and contact-times of 0·4 to 2·3 min. Hexafluorobenzene was readily detected in the complex mixture of products by its characteristic infrared absorption at 1536 cm.$^{-1}$,[2] and the yield was determined by gas–liquid chromatographic analysis. The best yield (14%) of hexafluorobenzene was obtained with a

[1] Part II, Birchall and Haszeldine, *J.*, 1959, 3653.
[2] Birchall and Haszeldine, *J.*, 1959, 13.
[3] Locke, Brode, and Henne, *J. Amer. Chem. Soc.*, 1934, **56**, 1726.
[4] Henne and Wiest, *J. Amer. Chem. Soc.*, 1940, **62**, 2051.
[5] Tarrant and Brown, *J. Amer. Chem. Soc.*, 1951, **73**, 1781.
[6] Ruh, U.S.P. 2,737,530/1956; *Chem. Abs.*, 1956, **50**, 10758g.

XUM

contact-time of 2·3 min. at a furnace temperature of 600°. Attempts to separate hexafluorobenzene from the products of pyrolysis by distillation were unsuccessful with the quantities used, but the pure compound was obtained by preparative-scale gas–liquid chromatography. Pyrolysis of 1-chloro-1,2-difluoroethylene over a nickel surface at 600—750° gave lower yields (1—2%) of hexafluorobenzene.

1,2-Dichlorodifluoroethylene was pyrolysed over nickel and over iron surfaces, in an atmosphere of nitrogen at temperatures of 450—1000°, but no hexafluorobenzene was produced. Under conditions leading to the elimination of chlorine, extensive carbonisation occurred and an intractable mixture of products was obtained. However, one experiment in which 1,2-dichlorodifluoroethylene was pyrolysed in the presence of hydrogen, in a platinum tube at 625°, gave hexafluorobenzene in *ca.* 2% yield.

It is emphasised that no attempts were made to examine all the reaction variables in the above pyrolyses, and it is clear that the yields reported could very probably be raised considerably.

The postulated formation of difluoroacetylene during the pyrolysis of chloro-1,2-difluoroethylene

$$CFCl{:}CFH \xrightarrow{-HCl} [C_2F_2] \longrightarrow C_6F_6$$

is supported by the observation that pyrolysis of trichloroethylene gives a quantitative yield of hexachlorobenzene; kinetic studies suggest that dichloroacetylene is an intermediate in this reaction.[7]

Difluoroacetylene has recently been reported as a product of the pyrolysis of difluoromaleic anhydride:[8]

$$2\ \begin{matrix} CF{\cdot}CO \\ \| \\ CF{\cdot}CO \end{matrix}\!\!>O \longrightarrow FC{:}CF + FC{:}C{\cdot}COF + 2CO_2 + CO$$

Isolation and characterisation of the difluoroacetylene was not achieved, and identification rests on mass-spectrographic analysis. The very limited studies so far reported on difluoroacetylene suggest that it decomposes vigorously with extensive carbonisation, even at low temperatures. The only product mentioned is an unknown structure C_4F_4, and it is not clear whether the possibility of the formation of hexafluorobenzene was considered. It is not known whether the decomposition of difluoroacetylene was spontaneous or induced by the presence of impurity.

On the other hand, monofluoroacetylene, prepared by pyrolysis of monofluoromaleic anhydride, is reported to trimerise spontaneously in the vapour phase to give a low yield of 1,2,4-trifluorobenzene, apparently without the formation of 1,3,5-trifluorobenzene.[9]

Experimental

All chromatography columns to which specific reference is made were packed with 30% w./w. of " dinonyl " phthalate on Celite.

Preparation of 1,2-*Dichlorodifluoroethylene.*—A sample of tetrachlorodifluoroethane (500 g.) in ethanol (150 ml.) was added during 2 hr. to a stirred suspension of activated zinc dust (1250 g.) in ethanol (800 ml.) at 30—40°. The volatile products were distilled continuously from the reactants and collected in traps cooled to −78°. The mixture was later heated under gentle reflux to ensure complete removal of the products. Redistillation gave dichlorodifluoroethylene (300 g.; 92%), b. p. 19—20·5° (Found: *M*, 134. Calc. for $C_2Cl_2F_2$: *M*, 133), shown by gas–liquid chromatography (2-m. column at room temperature) to contain 1,2-dichlorodifluoroethylene (64%) and 1,1-dichlorodifluoroethylene (36%).

A solution from sodium (6·0 g.) and ethanol (100 ml.) was added cautiously at room temperature to the dichlorodifluoroethylene mixture (300 g.) dissolved in ethanol (500 ml.). After a

[7] Goodall and Howlett, *J.*, 1954, 2599.
[8] Middleton, U.S.P. 2,831,835/1958; *Chem. Abs.*, 1958, **52**, 14658f.
[9] Middleton and Sharkey, *J. Amer. Chem. Soc.*, 1959, **81**, 803.

XUM

short induction period, a vigorous reaction commenced and continued for 15 min. The mixture was heated under reflux for 3 hr. and the volatile product was then distilled, dried (P_4O_{10}), and redistilled to give 1,2-dichlorodifluoroethylene (186 g.), b. p. 20° (Found: C, 18·3%; *M*, 133. Calc. for $C_2Cl_2F_2$: C, 18·1%; *M*, 133), identified by infrared spectroscopy. Chromatographic analysis (4-m. column at room temperature) indicated the presence of only one component.

Preparation of Chloro-1,2-difluoroethylene.—1,2-Dichlorodifluoroethylene (50 g.; 0·38 mole) and hydrogen bromide (31 g.; 0·38 mole), in a 20-l. " Pyrex " bulb, were irradiated by a 500-w mercury discharge tube, inserted into a silica tube in the centre of the bulb. The reaction, which was followed by pressure readings, was complete after 1 hr. Distillation gave *1-bromo-1,2-dichloro-1,2-difluoroethane* (75 g.; 93%) (Found: C, 11·4; H, 0·5%; *M*, 215. $C_2HBrCl_2F_2$ requires C, 11·5; H, 0·5%; *M*, 214), b. p. 98°, n_D^{20} 1·4307.

The bromo-compound was added gradually to a stirred suspension of activated zinc dust (160 g.) in ethanol (110 ml.) at 30—40°. At the end of the reaction, water was added and the product was distilled, dried (P_4O_{10}), and redistilled to give 1-chloro-1,2-difluoroethylene (31 g.; 94%) (Found: C, 24·7; H, 1·0%; *M*, 99. Calc. for C_2HClF_2: C, 24·4; H, 1·0%; *M*, 98·5), b. p. −15° (Ruh and Rector [10] give b. p. −16° to −14·5°/744 mm.). The product was shown to be a *cis-trans* mixture by gas–liquid chromatography (resolved easily on a 4-m. column at room temperature). It showed C=C stretching absorption at 1709 and 1721 $cm.^{-1}$ (doublet).

Pyrolysis of Chloro-1,2-difluoroethylene.—The apparatus for pyrolysis over platinum was essentially that described earlier for the pyrolysis of tribromofluoromethane.[2] 1-Chloro-1,2-difluoroethylene vapour was introduced in a slow stream of nitrogen (100 ml./hr.), and the products were collected in traps at −78° and −196°. Under the best conditions found, the olefin (94·0 g.) was introduced into the platinum tube at a constant rate of 6·5 g./hr. (contact-time, 2·3 min.) with a furnace temperature of 600°. Hydrogen chloride (14·7 g.; 42%) and unreacted chloro-1,2-difluoroethylene (35·6 g.; 38%) were removed by distillation. The remaining material was shown by infrared spectroscopy and gas–liquid chromatography to contain hexafluorobenzene (5·3 g.; 9%; 14% on olefin transformed) and several other components. Gas–liquid chromatographic equipment was carefully calibrated with a pure sample of hexafluorobenzene.[2] Distillation of the products followed by preparative-scale gas–liquid chromatography (3-m. column) gave hexafluorobenzene (3·8 g.) (Found: C, 38·6%; *M*, 183. Calc. for C_6F_6: C, 38·7%; *M*, 186), identified by infrared spectroscopy.

This result is compared with those of other experiments in the Table.

Temp.	590°	600°	620°	620°	650°
C_2HClF_2 (g./hr.)	6·5	6·5	6·5	13·0	32·5
C_2HClF_2, % recovered	44	38	29	45	65
C_6F_6, % net yield	11	14	8·5	6	5

Pyrolysis of 1-chloro-1,2-difluoroethylene over nickel was carried out similarly, a nickel tube of 18 mm. i.d. being used, heated over 40 cm. of its length in an electric furnace. Pyrolysis of the olefin at 650° with a flow rate of 27 g./hr. in a slow stream of nitrogen (100 ml./hr.) gave a 1—2% yield of hexafluorobenzene. Lower yields were obtained from experiments at other furnace temperatures and flow rates.

Pyrolysis of 1,2-Dichlorodifluoroethylene.—(a) *In nitrogen.* 1,2-Dichlorodifluoroethylene was similarly pyrolysed in the nickel tube, at 600—1000° and flow rates of 10—100 g./hr. Spectroscopic and chromatographic analysis of the products showed that no hexafluorobenzene was produced.

Pyrolysis at 450° and 550° in the nickel tube packed with clean iron gauze also failed to yield hexafluorobenzene.

(b) *In hydrogen.* 1,2-Dichlorodifluoroethylene (10·0 g./hr.) was pyrolysed in a stream of hydrogen (2·14 l./hr.) in the platinum tube at 625°. After a preliminary distillation, the product was shown by infrared spectroscopy and gas–liquid chromatography to contain hexafluorobenzene (*ca.* 2%).

The authors are indebted to Pennsalt Chemicals Corporation for a grant in support of this work.

FACULTY OF TECHNOLOGY, UNIVERSITY OF MANCHESTER. [*Received, December 19th*, 1960.]

[10] Ruh and Rector, U.S.P. 2,716,109/1956.

XUM

419. *Kinetics of the Reaction of Alkyl and Aryl Compounds of the Nickel Group with Pyridine.*

By F. Basolo, J. Chatt, H. B. Gray, R. G. Pearson, and B. L. Shaw.

Kinetic studies are reported of the reaction in ethanol solution between pyridine and several planar platinum(II), palladium(II), and nickel(II) compounds of the general formula $[MClR(PR'_3)_2]$. The relative rates of attainment of equilibrium of *trans*-$[MCl(o\text{-tolyl})(PEt_3)_2]$ with pyridine are approximately 5,000,000 : 100,000 : 1 where M is Ni(II), Pd(II), and Pt(II) respectively. The effect on the rates of equilibration of different groups *trans* to the chloro-group undergoing replacement shows that the *trans*-labilizing abilities of these ligands decrease as follows: $PMe_3 > PEt_3 \simeq H > PPr_3 >$ Me > phenyl $\simeq$ *p*-methoxyphenyl $\simeq$ *p*-chlorophenyl > biphenylyl > *o*-tolyl > mesityl $\simeq$ Cl. Both the electrostatic (polarization) and π-bonding theories of the *trans*-effect are needed to explain these results. Mesityl compounds always react more slowly than do analogous aryl derivatives. These observations are discussed in terms of probable mechanisms of planar substitution. Experimental details are also given for the synthesis of new compounds whose dipole moments are recorded.

Substitution (replacement) reactions of square-planar metal complexes have been studied kinetically, especially those of compounds of platinum(II) which react at rates suitable to be followed by ordinary techniques.[1] The results of these investigations indicate that solvent and/or reactant are involved in the rate-determining step. For reversible reactions of the type reported in this paper:

$$[MClR(PR'_3)_2] + py \rightleftharpoons [M(R)py(PR'_3)_2]^+ + Cl^- \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

(where R = alkyl, aryl, or hydrogen; R′ = alkyl)

the general rate law for the attainment of equilibrium can be expressed by the equation

$$k_{obs} = k_1 + k_2[py] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $k_{obs.}$ is a pseudo-first-order rate constant, k_1 is a first-order rate constant for solvent-controlled reaction, and k_2 is a second-order rate constant for reaction with pyridine.[2] This paper reports k_1 and k_2 values for a number of such reactions in ethyl alcohol solutions.

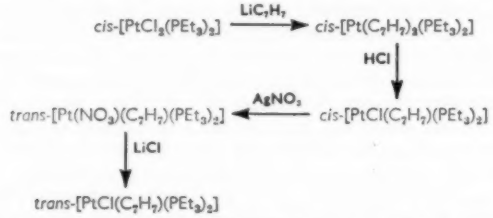
Neither k_1 nor k_2 is a simple rate constant since, for a reversible process, both forward and reverse reactions contribute to the attainment of equilibrium. It may then be expected that a part of k_1 and also of k_2 should depend on the chloride-ion concentration, which is certainly involved in the reverse reaction and increases markedly during the course of a kinetic study. Experimentally the effect of changing chloride concentration cannot be detected since a first-order course is followed throughout. This was also observed by Lamb[3] in his study of the reversible aquation of $[Rh(NH_3)_5Br]^{2+}$, and his explanation may be applicable here, namely, that changes in activity coefficients due to ionic-strength effects roughly cancel changes in concentration. Despite the complex nature of k_1 and k_2, they seem suitable for assessing the relative activating influence of substituents in a series of analogous compounds undergoing the same reaction, since they are independent of concentration over the ranges studied.

The results obtained permit (1) a comparison of rates of reaction of analogous nickel(II), palladium(II), and platinum(II) compounds; (2) an estimate of the *trans*-effect of different groups; (3) demonstration of a large steric effect on the rates of these reactions; and (4) comparison of rate constants and equilibrium constants.

[1] (*a*) Grinberg, *Russ. J. Inorg. Chem.*, 1959, **4**, 683; (*b*) Basolo, Gray, and Pearson, *J. Amer. Chem. Soc.*, 1960, **82**, 4200; and references therein.
[2] Gray and Olcott, unpublished work.
[3] Lamb, *J. Amer. Chem. Soc.*, 1939, **61**, 699.

XUM

General Method of Preparation of the Organometallic Complexes.—Many of the alkyl-, aryl-, and hydrido-metal complexes studied in this work have been described previously;[4-7] and many of the remainder were prepared by analogous methods. A new method was used to prepare the chloro-complexes *trans*-[PtClR(PEt_3)$_2$] (R = *o*-tolyl or mesityl). The reaction scheme is outlined below for the *o*-tolyl complexes.



The sterically hindered *cis*-[PtCl(*o*-tolyl)(PEt_3)$_2$] could not be converted into the *trans*-complex by treatment with a trace of triethylphosphine, in contrast with the complexes *cis*-[PtClR(PEt_3)$_2$] (R = Me, Ph, or *p*-tolyl) which were readily isomerised by this treatment. However, *cis*-[PtCl(*o*-tolyl)(PEt_3)$_2$] on treatment with silver nitrate gave only the *trans*-nitrato-complex; presumably the *cis*-nitrato-complex is formed initially but this rapidly changes to the more stable *trans*-form. Mesitylplatinum complexes behaved similarly. The nitrate complexes *trans*-[Pt(NO_3)R(PEt_3)$_2$] (R = *o*-tolyl, mesityl) were volatile, subliming slowly without decomposition above 160°/1 atm.

Experimental

Preparation of Organometallic Complexes.—The preparation and properties of the complexes studied in this paper and which have not been described previously[4-7] are given below. M. p.s were determined on a Kofler hot-stage and are corrected.

trans-*Di-(o-tolyl)bis(triethylphosphine)palladium*(II), [Pd(*o*-tolyl)$_2$(PEt_3)$_2$]. A 1·75N-solution of *o*-tolyl-lithium in ether (9·0 c.c.) was added at *ca.* −10° to a solution of *trans*-dibromobis(triethylphosphine)palladium(II) (3·0 g.) in benzene (16 c.c.). After 15 min. at *ca.* 10° benzene (30 c.c.) and water were added and the product was isolated from the organic phase. After one recrystallization from methyl alcohol and one from light petroleum (b. p. 40—80°) trans-*di-(o-tolyl)bis(triethylphosphine)palladium*(II) was obtained as needles (1·29 g.), m. p. 123—127° (decomp.) (Found: C, 59·65; H, 8·6. $C_{26}H_{44}P_2Pd$ requires C, 59·5; H, 8·45%).

trans-*Chloro-(o-tolyl)bis(triethylphosphine)palladium*(II), [PdCl(*o*-tolyl)(PEt_3)$_2$]. A solution of *trans*-di-(*o*-tolyl)bis(triethylphosphine)palladium(II) (0·84 g.) in benzene (5 c.c.) and ether (5 c.c.) was treated with a 1·00N-solution of hydrogen chloride in ether (1·61 c.c.). After 18 hr. at 20° the solution was evaporated to dryness and the residue recrystallized first from methyl alcohol, then from light petroleum (b. p. 40—60°), to give trans-*chloro-(o-tolyl)bis(triethylphosphine)palladium*(II) as prisms (0·67 g.), m. p. 86—88° (Found: C, 48·55; H, 7·95. $C_{19}H_{37}ClP_2Pd$ requires C, 48·65; H, 7·95%).

trans-*Nitrato-(o-tolyl)bis(triethylphosphine)platinum*(II), [Pt(NO_3)(*o*-tolyl)(PEt_3)$_2$]. A mixture of *cis*-chloro-(*o*-tolyl)bis(triethylphosphine)platinum(II) (3·43 g.), silver nitrate (1·2 g.), and ethyl alcohol (40 c.c.) was shaken for 3 hr. at 20°. The precipitated silver chloride was then filtered off, the filtrate evaporated to dryness, and the residue extracted with boiling light petroleum (b. p. 60—100°). The light petroleum extracts, on cooling, gave trans-*nitrato-(o-tolyl)bis(triethylphosphine)platinum*(II) as needles (2·83 g.), m. p. 188—190° (with sublimation above 160°) (Found: C, 39·0; H, 6·45; N, 2·65. $C_{19}H_{37}NO_3P_2Pt$ requires C, 39·05; H, 6·4; N, 2·4%).

A mixture of this nitrate complex (0·290 g.), pyridine (0·04 g.), and ether (10 c.c.) was boiled

[4] Chatt and Shaw, *J.*, 1959, 705, 4020.
[5] Chatt and Shaw, *J.*, 1960, 1718.
[6] Adams, Chatt, and Shaw, *J.*, 1960, 2047.
[7] Chatt, Duncanson, and Shaw, *Proc. Chem. Soc.*, 1957, 343; *Chem. and Ind.*, 1958, 859.

for 5 min. Benzene (5 c.c.) was then added and after the mixture had been warmed to 40° an excess of light petroleum (b. p. 60—80°) was added. The precipitate was filtered off and washed with light petroleum (b. p. 60—80°), to give *o-tolyl(pyridine)bis(triethylphosphine)platinum*(II) *nitrate* (0·261 g.) as colourless prisms, m. p. 190—192° (decomp.) (Found: C, 43·5; H, 6·55. $C_{24}H_{42}N_2O_3P_2Pt$ requires C, 43·45; H, 6·4%). The product was soluble in benzene or water and had a molar conductivity in nitrobenzene at 25° of 29·3 mho corresponding to a univalent-univalent electrolyte.

trans-*Chloro-(o-tolyl)bis(triethylphosphine)platinum*(II), $[PtCl(o\text{-tolyl})(PEt_3)_2]$. The above-mentioned nitrate (0·70 g.) and lithium chloride (1·5 g.) in acetone (20 c.c.) were heated under reflux for 30 min., then evaporated to dryness, water was added, and the product was isolated with ether. trans-*Chloro-(o-tolyl)bis(triethylphosphine)platinum*(II) was obtained as prisms (0·305 g.), m. p. 104—105°, from light petroleum (b. p. 60—80°) (Found: C, 41·2; H, 6·85. $C_{19}H_{37}ClP_2Pt$ requires C, 40·9; H, 6·7%).

o-Tolyl(pyridine)bis(triethylphosphine)platinum(II) nitrate (0·100 g.) in water (2 c.c.) was treated with sodium chloride (0·2 g.) and put aside. After 18 hr. at 20° *trans*-chloro-(*o*-tolyl)bis-(triethylphosphine)platinum(II) had crystallized as colourless needles (0·084 g.), m. p. 103—104°, identical with the preceding sample.

trans-*Nitrato(mesityl)bis(triethylphosphine)platinum*(II), $[PtNO_3(mesityl)(PEt_3)_2]$. A solution of *cis*-bromo(mesityl)bis(triethylphosphine)platinum(II) (1·89 g.) in benzene (30 c.c.) and ethyl alcohol (30 c.c.) was treated with a suspension of silver nitrate (0·61 g.) in ethyl alcohol (30 c.c.). The mixture was then shaken for 2 hr., after which the silver chloride was filtered off and the filtrate evaporated to dryness. The residue was recrystallized first from ethyl alcohol, then from light petroleum (b. p. 60—80°), to give trans-*nitrato(mesityl)bis(triethylphosphine)platinum*-(II) as prisms (1·55 g.), m. p. 146—147° (Found: C, 41·25; H, 6·85; N, 2·4. $C_{21}H_{41}NO_3P_2Pt$ requires C, 41·15; H, 6·75; N, 2·3%).

trans-*Chloro(mesityl)bis(triethylphosphine)platinum*(II), $[PtCl(mesityl)(PEt_3)_2]$. A mixture of the last-mentioned nitrate (0·70 g.), lithium chloride (1·15 g.), and acetone (25 c.c.) was heated under reflux for 20 min., then evaporated to dryness, and water was added. The residue was dried and recrystallized from light petroleum (b. p. 60—80°), to give trans-*chloro(mesityl)bis-(triethylphosphine)platinum*(II) as needles (0·43 g.), m. p. 196·5—197·5° (with sublimation into prisms) (Found: C, 43·1; H, 7·15. $C_{21}H_{41}ClP_2Pt$ requires C, 43·05; H, 7·05%).

cis- *and* trans-*Bromo(mesityl)bis(triethylphosphine)platinum*(II), $[PtBr(mesityl)(PEt_3)_2]$. *trans*-Dibromobis(triethylphosphine)platinum(II) (3·0 g.) and benzene (40 c.c.) were added to a Grignard reagent, prepared from magnesium (0·77 g.), a trace of iodine, 2-bromomesitylene (6·38 g.), and tetrahydrofuran (15 c.c.). The mixture was stirred at 20° for 50 min. and then heated under reflux for 20 min., cooled, and hydrolysed with dilute hydrobromic acid. The crude product isolated from the organic layer was extracted with hot light petroleum (b. p. 40—60°), leaving a residue of *cis*-bromo(mesityl)bis(triethylphosphine)platinum(II), which formed matted needles (0·51 g.), m. p. 184—186° from benzene–light petroleum (b. p. 60—80°) (Found: C, 39·65; H, 6·6. Calc. for $C_{21}H_{41}BrP_2Pt$: C, 40·0; H, 6·55%). The light petroleum (b. p. 40—60°) extract was evaporated to dryness and the residue recrystallized from light petroleum (b. p. 60—80°), to give trans-*bromo(mesityl)bis(triethylphosphine)platinum*(II) as needles (0·59 g.), m. p. 185·5—187° (with sublimation) (Found: C, 40·3; H, 6·6%).

Bromo(mesityl)-1,2-bisdiethylphosphinoethanenickel(II), $[NiBr(mesityl)(Et_2P{\cdot}CH_2{\cdot}CH_2{\cdot}PEt_2)]$. Dibromo-1,2-bisdiethylphosphinoethanenickel(II) (0·80 g.) was added to the Grignard reagent, prepared from magnesium (0·24 g.), tetrahydrofuran (15 c.c.), and 2-bromomesitylene (1·99 g.). Benzene (15 c.c.) was added and the resultant dark brown solution stirred at 15° for 10 min., then cooled to *ca.* −50° and hydrolysed by the slow addition of dilute hydrobromic acid. Ether was added and the product was isolated from the organic layer. *Bromo(mesityl)-1,2-bisdi-ethylphosphinoethanenickel*(II) was obtained as orange needles (0·69 g.), m. p. 172—174°, from benzene–light petroleum (b. p. 60—80°) (Found: C, 49·4; H, 7·6. $C_{19}H_{35}BrNiP_2$ requires C, 49·2; H, 7·6%).

trans-*Di-(4-biphenylyl)bis(triethylphosphine)platinum*(II), $[Pt(C_6H_4{\cdot}C_6H_5)_2(PEt_3)_2]$. *trans*-Dichlorobis(triethylphosphine)platinum(II) (2·00 g.) was added to the Grignard reagent, prepared from magnesium (0·48 g.), 4-bromobiphenyl (4·66 g.), tetrahydrofuran (20 c.c.), and benzene (25 c.c.). After the mixture had been heated under reflux for 3½ hr. it was cooled and hydrolysed with dilute hydrochloric acid, and the product was isolated from the benzene layer. trans-*Di-(4-biphenylyl)bis(triethylphosphine)platinum*(II) was obtained as prisms (1·45 g.), m. p. 209—

XUM

215° (decomp.), from light petroleum (b. p. 80—100°) or ethyl methyl ketone (Found: C, 59·0; H, 6·65. $C_{36}H_{46}P_2Pt$ requires C, 58·6; H, 6·55%).

trans-*Chloro*-(4-*biphenylyl*)*bis*(*triethylphosphine*)*platinum*(II). A solution of *trans*-di-(4-biphenylyl)bis(triethylphosphine)platinum(II) (0·60 g.) in benzene (5 c.c.) and ether (10 c.c.) was treated with a 0·425N-solution of dry hydrogen chloride in ether (2·77 c.c.). After 3 hr. at 20° the solution was evaporated to dryness and the residue recrystallized from light petroleum (b. p. 60—80°), giving trans-*chloro*-(4-*biphenylyl*)*bis*(*triethylphosphine*)*platinum*(II) (0·395 g.) as prisms, m. p. 116—118° (Found: C, 46·55; H, 6·4. $C_{24}H_{39}ClP_2Pt$ requires C, 46·5; H, 6·35%).

trans-*Chloro*-(p-*chlorophenyl*)*bis*(*triethylphosphine*)*platinum*(II), [PtCl(*p*-chlorophenyl)$(PEt_3)_2$]. *trans*-Di-(*p*-chlorophenyl)bis(triethylphosphine)platinum(II) (1·67 g.) in methylene chloride (18 c.c.) was treated with a 0·935N-solution of dry hydrogen chloride in ether (3·0 c.c., 1 mol.).

TABLE 1. *Dipole moments of some arylplatinum*(II) *and palladium*(II) *complexes in benzene at* 25°

	$10^5\omega$	Δ/ω	$-\Delta v/\omega$	$_TP$ *	$_EP$	$_OP$ *	μ * (D)
trans-[PdCl(*o*-tolyl)$(PEt_3)_2$]	4·362	2·597					
	6·229	2·600					
			(0·40)	334	(122)	194	3·1
trans-[$PtNO_3$(*o*-tolyl)$(PEt_3)_2$]	5·310	5·153					
	5·076	5·119					
			(0·55)	669	(114)	538	5·15
trans-[PtCl(*o*-tolyl)$(PEt_3)_2$]	3·990	1·348					
	7·202	1·335					
			(0·55)	240	(111)	112	2·35
trans-[$PtNO_3$(mesityl)$(PEt_3)_2$]	3·611	5·263					
	3·876	5·258					
			(0·55)	716	(123)	574	5·3
trans-[PtCl(mesityl)$(PEt_3)_2$]	4·436	1·430					
	5·301	1·434					
			(0·55)	262	(120)	124	2·45
trans-[PtBr(mesityl)$(PEt_3)_2$]	2·842	2·015					
	3·608	1·974					
			(0·58)	343	(123)	202	3·15
trans-[Pt(4-biphenylyl)$_2(PEt_3)_2$]	2·839	0·442					
			(0·45)	214	(186)	0	0
trans-[PtCl(4-biphenylyl)$(PEt_3)_2$]	3·582	1·833					
	4·454	1·879					
			(0·53)	330	(142)	167	2·85
trans-[PtCl(*p*-chlorophenyl)$(PEt_3)_2$]	4·542	0·482					
	7·466	0·462					
			(0·56)	152	(110)	26	1·1
trans-[Pt(*p*-methoxyphenyl)$_2(PEt_3)_2$]	4·106	1·058					
	4·864	1·044					
			(0·53)	245	(150)	73	1·9
cis-[Pt(*p*-methoxyphenyl)$_2(PEt_3)_2$]	5·193	8·503					
	6·433	8·524					
			(0·45)	1169	(150)	997	7·0
trans-[PtCl(*p*-methoxyphenyl)$(PEt_3)_2$]	4·037	2·072					
	4·452	2·067					
			(0·55)	326	(113)	196	3·1

* Calc. by using estimated values of densities and refractivities (see Chatt and Shaw [4]). Estimated values are given in parentheses.

After 1½ hr. the resultant solution was evaporated to dryness and the residue recrystallized from light petroleum (b. p. 40—60°), to give trans-*chloro*-(p-*chlorophenyl*)*bis*(*triethylphosphine*)-*platinum*(II) as prisms (1·28 g.), m. p. 110—111·5° (Found: C, 37·5; H, 5·95. $C_{18}H_{34}Cl_2P_2Pt$ requires C, 37·4; H, 5·95%).

cis- *and* trans-*Di*-(p-*methoxyphenyl*)*bis*(*triethylphosphine*)*platinum*(II), [$Pt(C_6H_4OMe)_2(PEt_3)_2$]. *trans*-Dichlorobis(triethylphosphine)platinum(II) (2·00 g.) in benzene (30 c.c.) was added to a Grignard reagent, prepared from magnesium (0·48 g.), *p*-bromoanisole (2·63 c.c.), a trace of iodine, and tetrahydrofuran (15 c.c.). The mixture was stirred at 20° for 50 min., then heated under reflux for 40 min., cooled, and hydrolysed with dilute hydrobromic acid. The crude product isolated from the organic layer was recrystallized from benzene–methyl alcohol, to give trans-*di*-(p-*methoxyphenyl*)*bis*(*triethylphosphine*)*platinum*(II) as prisms, m. p. 195—210° (decomp., with sublimation above 180°) (Found: C, 48·0; H, 7·0. $C_{26}H_{44}O_2P_2Pt$ requires C

48·35; H, 6·85%). The mother-liquors from this crystallization were evaporated to dryness and the residue recrystallized from methyl alcohol and then light petroleum (b. p. 80—100°). Thus was obtained cis-*di*-(p-*methoxyphenyl*)*bis*(*triethylphosphine*)*platinum*(II) as prisms (0·72 g.), m. p. 129—132° (Found: C, 48·35; H, 6·85%).

trans-*Chloro*-(p-*methoxyphenyl*)*bis*(*triethylphosphine*)*platinum*(II), [PtCl(C_6H_4OMe)(PEt_3)$_2$]. *trans*-Di-(*p*-methoxyphenyl)bis(triethylphosphine)platinum(II) (0·890 g.) in benzene (10 c.c.) and ether (15 c.c.) was treated with a 1·17N-solution of hydrogen chloride in ether (1·19 c.c.).

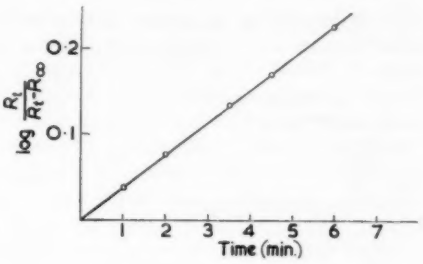


FIG. 1. *Pseudo-first-order rate analysis at 25°: C_5H_5N, 0·0018M; trans-*[PtClMe(PEt_3)$_2$], 0·0002M. (R_t *and* R_∞ *are the electrical resistances of the solution at time t and equilibrium, respectively.*)

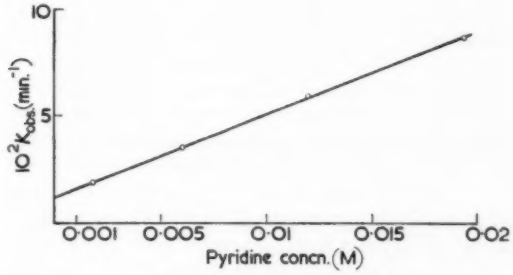


FIG. 2. *Dependence of* k_{obs} *on the concentration of pyridine in reaction with* 0·0002M-*trans*-[PtClMe(PEt_3)$_2$] *at* 25°.

After 2 hr. the solution was evaporated to dryness and the residue recrystallized from light petroleum (b. p. 60—80°) to give trans-*chloro*-(p-*methoxyphenyl*)*bis*(*triethylphosphine*)*platinum*(II) as needles (0·582 g.), m. p. 131—133·5° (Found: C, 40·05; H, 6·6. $C_{19}H_{37}ClOP_2Pt$ requires C, 39·75; H, 6·5%).

Determination of Dipole Moments.—These were determined as described previously;[4] the measurements and estimated values (shown in parentheses) are recorded in Table 1. The

TABLE 2. *Comparison of the rates of attainment of equilibrium of similar nickel*(II), *palladium*(II), *and platinum*(II) *complexes at* 25°.

Complex [a]	Range of initial 10^3[py] (M)	k_1 (min.$^{-1}$)
trans-[NiCl(*o*-tolyl)(PEt_3)$_2$]	1·24—6·2	2000 [b]
trans-[PdCl(*o*-tolyl)(PEt_3)$_2$]	1·24—6·2	35 [b]
trans-[PtCl(*o*-tolyl)(PEt_3)$_2$]	0·9—6·2	4×10^{-4}
trans-[NiCl(mesityl)(PEt_3)$_2$]	1·24—6·2	1·2
trans-[PtCl(mesityl)(PEt_3)$_2$]	0·9—6·2	7×10^{-5}
[NiBr(mesityl)(PEt_2·CH_2·CH_2·PEt_2)]	1·24—6·2	20 [b]
cis-[PtBr(mesityl)(PEt_3)$_2$]	0·9—6·2	3×10^{-4}

[a] The initial concentration of complex was 0·0004M. [b] Rate constants estimated from data at temperatures ranging from −80° to 0°.

margin of error is less than +0·2 D for dipole moments between 5·5 and 2·5 D. For dipole moments <2·5 D the margin of error will be greater than this but is difficult to estimate. The errors in determining small dipole moments are largely due to the uncertainty in the magnitude of the atom polarization which has been assumed to be 15% of the electron polarization in Table 1 but may be higher than this in complex compounds.

Determination of Reaction Rates and Equilibrium Constants.—The reactions with pyridine were followed by measuring changes in the electrical conductivity of an ethanol solution of the reactants.[12] The concentration of the complex was in the range 0·0002—0·002M and the

XUM

pyridine concentration was varied between 0·001M and 0·02M. The conductance change corresponded to the reversible reaction:

$$[PtClR(PEt_3)_2] + py \rightleftharpoons [PtR(py)(PEt_3)_2]^+ + Cl^-$$

in which the equilibrium favours the left-hand side. The rate of attainment of equilibrium in all cases was of pseudo-first order, as shown in Fig. 1 for *trans*-$[PtCl(Me)(PEt_3)_2]$. The variation of the pseudo-first-order rate constants (k_{obs}) with initial pyridine concentration was consistent

TABLE 3. trans-*Effect*: *rates of attainment of equilibrium between pyridine and complexes of the types* A *and* B *in ethanol at* 25°.

trans-Ligand X	Range of initial 10^3[py] (M)	k_1 (min.$^{-1}$)	k_2 (mole^{-1} l. min.$^{-1}$)
(A) *cis*-$[PtCl_2X_2]$ [a]			
PMe_3	0·9—6·2	5 [b]	—
PEt_3	0·9—6·2	1 [b]	$2·3 \times 10^2$ [b]
PPr_3	0·9—6·2	5×10^{-1} [b]	1×10^2 [b]
(B) *trans*-$[PtClX(PEt_3)_2]$ [c]			
H	1·24—6·2	1·1 [b]	$2·5 \times 10^2$ [b]
Me [c]	1·24—37·2	1×10^{-2}	4
Ph	0·9—6·2	2×10^{-3}	$9·5 \times 10^{-1}$
p-Chlorophenyl	0·9—6·2	2×10^{-3}	9×10^{-1}
p-Methoxyphenyl	0·9—6·2	$1·7 \times 10^{-3}$	$7·8 \times 10^{-1}$
4-Biphenylyl	0·9—6·2	1×10^{-3}	$5·8 \times 10^{-1}$
o-Tolyl	0·9—6·2	4×10^{-4}	1×10^{-1}
Mesityl	0·9—6·2	7×10^{-5}	$2·2 \times 10^{-2}$
Cl	0·9—6·2	6×10^{-5}	$2·4 \times 10^{-2}$

[a] Initial concn. of complex, 0·0004M. [b] Rate at 0°; reaction is too fast to measure at 25°. [c] This complex was also examined for 0·0002—0·001M-solutions and the pyridine concentration varied from 0·062 to 0·124M.

TABLE 4. cis-*Effect*: *rates of attainment of equilibrium in the reaction of pyridine with complexes of the types* A, B, *and* C *in ethanol at* 0°.

cis-Ligand X	Range of initial 10^3[py] (M)	k_1 (min.$^{-1}$)
(A) *cis*-$[PtClX(PEt_3)_2]$ [a]		
Me	0·9—6·2	3·6
Ph	0·9—6·2	2·3
p-Tolyl	0·9—6·2	3
o-Tolyl [b]	0·9—18·6	$5·2 \times 10^{-3}$
Mesityl [c]	0·9—6·2	$2·5 \times 10^{-5}$
Cl	0·9—6·2	1

cis-Ligand X	Range of initial 10^3[py] (M)	k_1 (min.$^{-1}$)
(B) *trans*-$[PtHClX_2]$ [a]		
PEt_3	1·24—6·2	1·1
PEt_2Ph	1·24—6·2	0·8
$PEtPh_2$	1·24—6·2	2
PPh_3	1·24—6·2	*d*
(C) *trans*-$[PtClMeX_2]$ [a]		
PMe_3	0·9—6·2	$1·5 \times 10^{-1}$
PEt_3 [b]	1·24—37·2	1×10^{-2}

[a] The initial concn. of complex was 0·0004M. [b] This complex was also examined in 0·0002—0·001M-solutions with pyridine concns. of 0·062—0·124M. [c] This complex was the bromide, *cis*-$[PtBr(mesityl)(PEt_3)_2]$. [d] Reaction is too fast to measure at 0°.

TABLE 5. *Comparison of rate constants and concentration equilibrium constants for the reaction with pyridine of some platinum*(II) *complexes in ethanol at* 25°.

Complexes	k_1 (min.$^{-1}$)	$K_{eq.}$	Complexes	k_1 (min.$^{-1}$)	$K_{eq.}$
trans-$[PtHCl(PEt_3)_2]$	1·1 (at 0°)	0·03	*cis*-$[PtClPh(PEt_3)_2]$	2·3	0·15
trans-$[PtClMe(PEt_3)_2]$	1×10^{-2}	0·15	*cis*-$[PtCl(o\text{-tolyl})(PEt_3)_2]$	$3·8 \times 10^{-2}$	0·10
trans-$[PtClPh(PEt_3)_2]$	2×10^{-2}	0·02	*cis*-$[PtBr(mesityl)(PEt_3)_2]$	3×10^{-4}	0·01
cis-$[PtClMe(PEt_3)_2]$	3·6 (at 0°)	0·3			

with the expression $k_{obs} = k_1 + k_2[py]$, since a plot of k_{obs} against pyridine concentration for *trans*-$[PtClMe(PEt_3)_2]$ gives a straight line with a non-zero intercept (Fig. 2). Similar plots were obtained for all the complexes studied and the rate constants k_1 and k_2 extracted are reported in Tables 2—4.

Equilibrium concentrations of products were calculated from conductance measurements and the concentration equilibrium constants resulting are reported in Table 5. Conductance was directly related to concentration only in the case of the isolable compound

XUM

$[Pt(o\text{-tolyl})(py)(PEt_3)_2]NO_3$ which gave a molar conductance of 34 cm.^{2} mole^{-1} ohm^{-1} in the concentration range used in the kinetic studies. This value of the molar conductance was used as equal to that of $[PtR(py)(PEt_3)_2]Cl$ in calculating the equilibrium constants. The constancy of these equilibrium constants over a range of pyridine concentrations was taken to justify the proportionality between conductance and concentration for the non-isolable chloride salts.

Discussion

The kinetic data in Table 2 afford a unique quantitative comparison of rates of reaction of analogous nickel(II), palladium(II), and platinum(II) compounds. The ratio of rates for *trans*-$[MCl(o\text{-tolyl})(PEt_3)_2]$ compounds is approximately 5,000,000 : 100,000 : 1 where M is Ni, Pd, and Pt respectively. The large difference in lability between platinum(II) and nickel(II) is consistent with a mechanism in which groups above and below the plane move in to displace the halide ion,[8] since nickel(II) is known to expand its co-ordination number more easily than platinum(II). It is also consistent that *trans*-$[NiCl(mesityl)(PEt_3)_2]$ reacts only about 20,000 times faster than *trans*-$[PtCl(mesityl)(PEt_3)_2]$. Thus by blocking the positions above and below the plane of the complex with a mesityl group,[5] nickel(II) is made much less labile than platinum(II), and in fact the rate differences then resemble those between octahedral cobalt(III) and iridium(III) complexes. For example, the relative rates of acid-hydrolysis of $[M(NH_3)_5Br]^{2+}$ complexes are about 4000 : 1 when M = Co and Ir respectively.[9]

Table 3 summarizes data showing how k_1 and k_2 depend on the ligand in *trans*-position to the chlorine atom. By using either k_1 or k_2 as a measure, the *trans*-labilizing ability (*trans*-effect) of the ligands in this particular equilibration reaction is found to decrease in the order: $PMe_3 > PEt_3 \approx H > PPr_3 >$ Me > phenyl $\approx$ *p*-methoxyphenyl $\approx$ *p*-chlorophenyl > biphenyl > *o*-tolyl > mesityl $\approx$ Cl.

There are two main hypotheses on the nature of the *trans*-effect.

Grinberg and others of the Russian school consider it to be mainly electrostatic in origin,[10] and to depend on the polarizability of the ligand. Thus the more polarizable the ligand the greater the *trans*-effect.

The second hypothesis suggests that large *trans*-effects are produced by ligands capable of dative π-bonding to the metal.[11,12] The large *trans*-effects of the trialkylphosphines are well known and have been attributed to this π-bonding which enhances nucleophilic attack and/or stabilizes a five-co-ordinated transition state.

The relative rates of reaction of complexes with *trans*-groups H, Me, phenyl, and Cl are approximately 100,000 : 200 : 30 : 1. Since π-bonding is not expected to be very important in binding these groups to the metal, this rapid decrease in rate must be mainly electrostatic in orgin. This is supported by the rapid decrease in dipole moment along the series of compounds *trans*-$[PtClR(PEt_3)_2]$ whose moment are R = H (4·2 D), Me (3·4 D), Ph (2·6 D), and Cl (0 D).

It is of interest that hydrogen (or hydride ion) has such a high *trans*-effect. Indeed it causes more rapid substitution in the position *trans* to itself than any other anionic ligand we have studied. The hydride ion, because of its substantial polarizability, may induce a strong polarization of the positive platinous ion which causes the repulsion of the *trans*-ligand according to the mechanism suggested by Grinberg.[10] We would expect that the large electrostatic effect of the hydride ion would be apparent as a large ligand field strength. Recent work [13] has confirmed this: both hydride ion and methide ion cause large ligand field splittings of the *d*-energy levels in ruthenium(II) complexes. The

[8] Basolo and Pearson, "Mechanism of Inorganic Reactions," Wiley and Sons, New York, 1958, pp. 186—190.
[9] Ref. 8, p. 122.
[10] Grinberg, *Ann. Inst. Platine U.S.S.R.*, 1932, **10**, 58; see ref. 8, p. 177.
[11] Chatt, Duncanson, and Venanzi, *Chem. and Ind.*, 1955, 749; *J.*, 1955, 4456.
[12] Orgel, *J. Inorg. Nuclear Chem.*, 1956, **2**, 137.
[13] Chatt and Hayter, *J.*, 1961, 772.

XUM

development of negative charge on the side of the platinous ion *trans* to the hydride ion should also lead to long bonds of considerable ionic character between the metal and the *trans*-ligand. This has been observed in *trans*-[$PtHBr(PEt_3)_2$] where the distance Pt–Br is 2·56 Å, to be compared with the radius sum of 2·43 Å.[14]

Data in Table 4 show that the reactivity of *cis*-[$PtClR(PEt_3)_2$] varies only slightly with changes in R. Thus for R = Cl, Ph, and Me the relative rates are 1, 2·3, and 3·6, increasing in the same sequence but very much more slowly than in the *trans*-series of complexes. This shows clearly the directional nature of this activating effect for groups such as H, Me, Ph, and Cl which must act almost entirely by induction.

It is interesting that in *trans*-[$PtCl_2(C_2H_4)(NHMe_2)$] the dimethylamine is very readily replaced by other groups owing to the high *trans*-effect of the ethylene, yet in contrast to the bromohydride mentioned above the Pt–N bond is of normal length {2·02 Å,[15] very similar to the distance 2·06 Å in Magnus's green salt $[Pt(NH_3)_4][PtCl_4]$}.[16] In this case we consider the rapid substitution to be mainly an effect of dative π-bonding by the ethylene.[11,12]

We can thus distinguish two electronic mechanisms of the *trans*-effect; (1) polarization of the metal ion by electrostatic forces resulting from electron release by the ligand *via* the σ-bond; (2) polarization of the metal ion by dative π-bonding to a suitable ligand, *i.e.*, electron release by the metal *via* the π-bond. Hydride ion and ethylene are examples of ligands with high *trans*-effects promoted mainly by mechanisms (1) and (2) respectively. There is also the possibility that both effects may operate with some ligands (*e.g.*, iodide ion) and in combination give a strong *trans*-effect.

It is interesting that *para*-substituents, X in *trans*-[$PtCl(p\text{-}C_6H_4X)(PEt_3)_2$] (X = H, Ph, OMe, Cl), hardly affect the rate of displacement of chloride ion. This supports the above observation that hydrogen and hydrocarbon radicals must exert their *trans*-effects mainly through induction. The inductive effects of the groups X should be very weak when they reach the platinum atom and so have little effect on the rate. On the other hand, if dative π-bonding were essential to a high *trans*-effect the *para*-substituent, X, would affect the rates considerably, because dative π-bonding would be very sensitive to the widely different and strongly transmitted mesomeric effects of the groups X.

In contrast, substituents in the *ortho*-position of the phenyl group do markedly affect the rate of reaction. Molecular models indicate that this is largely due to shielding of the central metal. For example, with the mesityl compound the aromatic ring is forced out of the plane of the complex so that two methyl groups occupy positions above and below the plane.[5] This will hinder the approach of a nucleophilic reagent and thus retard the rate of displacement. Since the results show that both k_1 and k_2 are affected, this supports the view that k_1 is a solvent displacement process and not just a bond-cleavage dissociation path. It is of interest that the steric effect is greater for *cis*- than for *trans*-isomers. Thus, for [$PtClR(PEt_3)_2$] where R = phenyl, *o*-tolyl, and mesityl, the relative rates of reaction for the *cis*-isomers are 100,000 : 200 : 1 whilst for the *trans*-isomers they are 30 : 6 : 1 respectively.* Scale molecular models suggest that the formation of a square-pyramidal intermediate by the approach of nucleophilic groups along the *z*-axis of either isomer is extremely difficult, if not impossible. Further, the same steric effect would be expected for both isomers. However, a nucleophilic approach at a slight angle in the direction of the chloro-group leading to a trigonal bipyramidal intermediate is possible in both cases and the steric hindrance would be much larger for the *cis*- than for the *trans*-isomer. The results therefore suggest a displacement process *via* a trigonal bipyramidal intermediate for these hindered complexes.

* When R was mesityl the *cis*-compound was a bromide, but kinetically there is little difference between the reactivities of chlorides and bromides of this type.

[14] Owston, Partridge, and J. M. Rowe, *Acta Cryst.*, 1960, **13**, 246.
[15] Alderman, Owston, and J. M. Rowe, *Acta Cryst.*, 1960, **13**, 149.
[16] Atoji, Richardson, and Rundle, *J. Amer. Chem. Soc.*, 1957, **79**, 3017.

XUM

The decrease in *trans*-effect of trialkylphosphines with increasing chain length of the alkyl groups is probably due to increased steric hindrance, because similarly a slightly larger effect is found in the compounds where both trialkylphosphine ligands are in the *cis*-position to the chloride ion being replaced (compare the last two compounds in Table 3 with the last two in Table 4).

The replacement of a halide by pyridine in these complexes is reversible in ethyl alcohol solution. It was not possible to isolate complexes of the type $[PtR(py)(PEt_3)_2]Cl$ from the reaction mixtures since the equilibrium favours the non-ionic compound. With nitrato-complexes, however, the reaction with pyridine goes to completion and salts $[PtR(py)(PEt_3)_2]NO_3$ can be isolated. This can be converted into the non-ionic chloro-complex by adding chloride ion.

It can be seen from Table 5 that the equilibrium constants for the reaction of pyridine with several platinum complexes vary very much less than the rate constants.

This investigation was partly supported by a grant from the U.S. Atomic Energy Commission under Contract AT (11-1)-89-project No. 2. We thank Miss I. Bates for assistance in measuring the dipole moments, and A. E. Field and M. L. Searle for other experimental assistance. One of us (H. B. G.) also thanks the National Science Foundation for a fellowship.

NORTHWESTERN UNIVERSITY, EVANSTON, ILLINOIS, U.S.A.
AKERS RESEARCH LABORATORIES, IMPERIAL CHEMICAL INDUSTRIES LIMITED,
THE FRYTHE, WELWYN, HERTS. [*Received, September 20th*, 1960.]

---

420. *Thermodynamics of Ion Association. Part VII.*[1] *Some Transition-metal Oxalates.*

By A. MCAULEY and G. H. NANCOLLAS.

Thermodynamic equilibrium constants for the association, in aqueous solution, of nickel, cobalt, and manganese ions with the oxalate ion have been determined by a precise e.m.f. method between 0° and 45°. ΔG, ΔH, and ΔS for the reaction $M^{2+} + C_2O_4^{2-} \rightleftharpoons MC_2O_4$ have been calculated and ΔC_p has been estimated from the variation of ΔH with temperature. The thermodynamic quantities are discussed.

PREVIOUS parts of this series have been concerned mainly with ion pairs of only moderate stability. The present work extends the available thermodynamic data to the much more stable oxalate complexes of bivalent transition-metal ions which are known to follow the Irving–Williams order of stability. The identification of complex species present in such solutions is made difficult by the low solubility of the salts. In the presence of an excess of oxalate the solubility increases owing to the formation of increasing amounts of $M(C_2O_4)_2^{2-}$, but we are interested in complexes in which a single anion is associated with each metal ion. Studies of copper oxalate have shown that, with careful control of experimental conditions, supersaturated solutions may be prepared which are stable for long periods.[2] This technique has been extended to cobalt, nickel, and manganese oxalate in the present work, and measurements have been made by using the cell

$$H_2\text{–Pt}|MCl_2,H_2C_2O_4,NaOH|AgCl\text{–Ag}$$

Only in the case of cobalt was it necessary seriously to limit the concentrations to prevent precipitation.

[1] Part VI, Nair and Nancollas, *J.*, 1959, 3934.
[2] McAuley and Nancollas, *Trans. Faraday Soc.*, 1960, **56**, 1165.

XUM

Experimental

Concentrations of stock solutions prepared from " AnalaR " metal chlorides were determined by gravimetric analysis of the chloride as silver chloride; duplicate determinations agreed to within 0·02%. " AnalaR " oxalic acid was recrystallised three times from conductivity water (analysis, 99·9% pure). Hydrochloric acid was constant-boiling material. Carbonate-free sodium hydroxide, prepared from a saturated solution suitably diluted with carbon dioxide-free conductivity water, was standardised both by volume- and by weight-titration against weighed samples of potassium hydrogen phthalate. The apparatus and experimental technique have been described previously.[3] Measurements were made with solutions, stable for at least 24 hr., containing known concentrations of oxalic acid, sodium hydroxide, and the metal chloride. To prevent precipitation, the metal chloride was added slowly only when the other ingredients had been made up nearly to the required volume. E.m.f. readings were constant to within 20 μv.

Results and Discussion

Since only the second thermodynamic dissociation constant of oxalic acid, $K_2 = a_{H^+}a_{C_2O_4^{2-}}/a_{HC_2O_4^-}$, had been determined accurately over a range of temperature,[4] it was necessary to obtain the corresponding values of $K_1 = a_{H^+}a_{HC_2O_4^-}/a_{H_2C_2O_4}$. The first dissociation is rather extensive and measurements were made with a mixed acid cell

$$H_2\text{–Pt}|H_2C_2O_4(m_1),\ HCl(m_4)|AgCl\text{–Ag}$$

the e.m.f. of which is given by

$$E' = E^0 - k \log a_{H^+}a_{Cl^-}$$

or

$$-\log [H^+] = (E' - E^0)/k + \log m_4 + \log \gamma_{H^+}\gamma_{Cl^-}$$

where m represents molality, γ activity coefficient, and $k = 2{\cdot}3026\ RT/F$. By using expressions for total oxalate $m_1 = [H_2C_2O_4] + [HC_2O_4^-] + [C_2O_4^{2-}]$, electroneutrality

Table 1. *Dissociation constant of oxalic acid.*

10^3m_1	10^3m_4	$(E' - E^\circ)$	$10^3[H^+]$	10^3I	$10^5[C_2O_4^{2-}]$	10^4X	10^5Y
2·9641	2·3993	0·29430	5·1574	5·196	3·842	2·457	1·454
3·8007	2·4028	0·29102	5·9097	5·953	4·362	3·048	1·824
3·6686	4·0032	0·27279	7·3331	7·368	3·466	4·309	2·591
3·5414	4·1377	0·27192	7·3375	7·371	3·329	4·488	2·572
7·6610	5·5797	0·25245	12·1490	12·195	4·553	9·614	5·606
4·7096	4·2582	0·26780	8·4721	8·511	3·899	5·475	3·249
4·2650	4·9781	0·26295	8·7793	8·813	3·416	5·808	3·433
5·0901	4·2715	0·26681	8·8099	8·851	4·068	5·806	3·456
1·9442	1·5601	0·31524	3·4178	3·454	3·658	1·126	0·727

Temp.	0°	15°	25°	35°	45°
10^3k_1	5·70	5·60	5·60	5·18	5·07

$[H^+] = [HC_2O_4^-] + 2[C_2O_4^{2-}] + m_4$, and ionic strength $I = [H^+] + [C_2O_4^{2-}]$, a graphical solution similar to that described by Speakman [5] was applied, leading to an equation

$$Y = XK_1 + K_1K_2$$

in which

$$X = \frac{[H^+]\gamma_2(m_1 - [H^+] - m_4)}{2m_1 - [H^+] + m_4}$$

and

$$Y = \frac{([H^+] - m_4)[H^+]^2\gamma_1^2\gamma_2}{2m_1 - [H^+] + m_4}$$

[3] Nair and Nancollas, *J.*, 1958, 4144.
[4] Robinson and Stokes, " Electrolyte Solutions," Butterworths, London, 1955.
[5] Speakman, *J.*, 1940, 856.

Activity coefficients were obtained from the Davies equation [6]

$$-\log \gamma_z = Az^2[I^{\frac{1}{2}}/(1 + I^{\frac{1}{2}}) - 0{\cdot}2I] \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Fig. 1 shows the good linear relation between X and Y at each temperature. The results at 25° are detailed in Table 1, which includes only the K_1 values at the other temperatures. At 25°, the value agrees very well with $5{\cdot}36 \times 10^{-2}$, obtained from conductivity measurements.[4]

The concentration of hydrogen ions in the cell

$$H_2\text{–Pt}|H_2C_2O_4(m_1),\ NaOH(m_2),\ MCl_2(m_3)|AgCl\text{–}Ag$$

is given by

$$-\log [H^+] = (E' - E^0)/k + \log 2m_3 + \log \gamma_{H^+}\gamma_{Cl^-}$$

The concentrations of ionic species were obtained from: $m_1 = [H_2C_2O_4] + [HC_2O_4^-] + [C_2O_4^{2-}] + [MC_2O_4]$, $m_3 = [M^{2+}] + [MC_2O_4]$, the electroneutrality condition $[H^+] + 2[M^{2+}] + m_2 = [HC_2O_4^-] + 2[C_2O_4^{2-}] + 2m_3$, and K_1 and K_2 for oxalic acid. Studies on the association between the nickel ion and the malonate and substituted malonate anions both at low concentration and at a number of constant ionic strengths up to $I = 0{\cdot}2$ have

FIG. 1. *Plots of X against Y. (The lines are displaced along the y-axis for clarity.)*

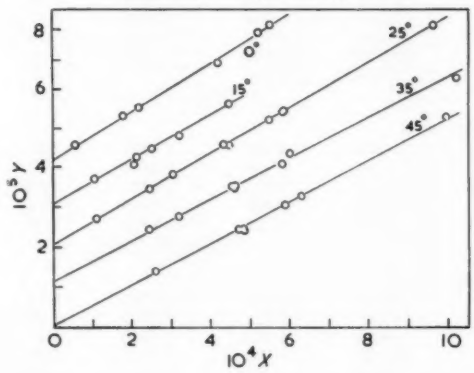
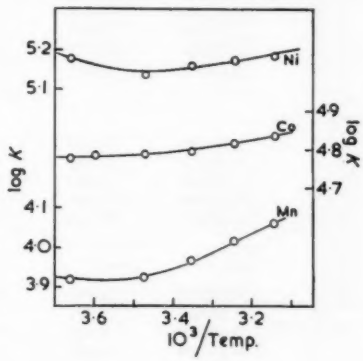


FIG. 2. *Plots of* log K *against* T^{-1}. *(Right-hand ordinates refer to* CoC_2O_4.*)*



shown that equation (1) represents the activity coefficients very satisfactorily.[7] The same equation has been used in the present work. T.I.P. programmes were constructed for a high-speed DEUCE electronic computer leading to the calculation of thermodynamic association constants $K = \{MC_2O_4\}/\{M^{2+}\}\{C_2O_4^{2-}\}$ by successive approximations of I. Three such approximations were usually carried through, giving 0·1% reproducibility in I. Table 2 shows the good constancy of K at each temperature.

The K values at 25° may be compared with those obtained from conductivity measurements: [8] $K(NiC_2O_4) = 2 \times 10^5$; $K(CoC_2O_4) = 5{\cdot}1 \times 10^4$; and $K(MnC_2O_4) = 8{\cdot}1 \times 10^3$; and, from solubilities, $K(MnC_2O_4) = 9{\cdot}1 \times 10^3$. Plots of log K against T^{-1} in Fig. 2 are curved, indicating a non-zero ΔC_p. This has often been observed in precise measurements on the dissociation of weak acids, but the present is one of the few cases in which detectable values of ΔC_p have been found for reactions involving metal-ion complexes. The variation of log K with temperature may be expressed by the equation $\log K = a + bT + cT^2$, in which the values of the three parameters are as in Table 3. The calculated K values have a maximum difference of 3% from the observed values.

[6] Davies, *J.*, 1938, 2093.
[7] Brannan and Nancollas, unpublished work.
[8] Davies, *Discuss. Faraday Soc.*, 1957, **24**, 83; *J.*, 1938, 2098.

XUM

TABLE 2. *E.M.F. measurements.*

Nickel oxalate

Experiment	1	2	3	4	5
10^3m_1	2·9569	3·5174	2·4884	3·2920	1·4138
10^3m_2	0·9450	1·1136	0·8777	1·0339	0·9226
10^3m_3	3·6011	4·3440	3·1053	3·9512	3·1629

Expt.	$(E' - E^\circ)$	10^3I	$10^3[H^+]$	$10^4[HC_2O_4^-]$	$10^5[C_2O_4^{2-}]$	$10^3[MC_2O_4]$	$10^{-5}K$
			Temp. = 0°				
1	0·25048	9·630	4·0397	8·282	1·914	2·0586	1·53
2	0·24226	11·574	4·8259	9·570	1·913	2·4721	1·62
3	0·25808	8·298	3·3479	6·809	1·851	1·7539	1·46
4	0·24607	10·598	4·4763	9·461	2·006	2·2620	1·52
5	0·27336	8·467	1·7207	1·750	0·929	1·2248	1·43
						Mean $K = 1·51 \pm 0·05$	
			Temp. = 15°				
1	0·26490	9·789	3·9568	9·038	2·014	1·9789	1·36
2	0·25630	11·781	4·7179	10·553	2·041	2·3677	1·42
3	0·27287	8·423	3·2842	7·404	1·936	1·6914	1·32
4	0·26008	10·717	4·4136	10·036	2·038	2·2015	1·44
5	0·28880	8·510	1·6996	1·953	6 988	1·2036	1·33
						Mean $K = 1·37 \pm 0·04$	
			Temp. = 25°				
1	0·27432	9·822	3·9371	9·222	1·919	1·9608	1·42
2	0·26539	11·808	4·7014	10·707	1·932	2·3529	1·50
3	0·28243	8·418	3·2839	7·409	1·798	1·6923	1·44
4	0·26940	10·772	4·3831	10·319	1·962	2·1729	1·47
5	0·29901	8·521	1·6932	2·014	0·950	1·977	1·39
						Mean $K = 1·44 \pm 0·03$	
			Temp. = 35°				
1	0·28403	9·920	3·8795	9·706	1·826	1·9087	1·44
2	0·27470	11·889	4·6499	11·113	1·806	2·3081	1·57
3	0·29240	8·499	3·2369	7·814	1·713	1·6494	1·46
4	0·27884	10·848	4·3349	10·703	1·833	2·1309	1·54
5	0·30941	8·553	1·6756	2·178	0·923	1·1810	1·42
						Mean $K = 1·49 \pm 0·06$	
			Temp. = 45°				
1	0·29365	9·989	3·8401	10·058	1·728	1·8724	1·48
2	0·28406	11·981	4·5978	11·572	1·721	2·2598	1·60
3	0·30227	8·553	3·2060	8·094	1·619	1·6210	1·51
4	0·28829	10·920	4·2933	11·070	1·731	2·0928	1·60
5	0·31977	8·577	1·6627	2·300	0·887	1·1688	1·48
						Mean $K = 1·53 \pm 0·05$	

Cobalt oxalate

Expt.	1	2	3	4	5	6	7	8	9
10^4m_1	10·6015	7·5201	9·9339	4·6320	4·4061	3·3415	4·3336	4·0907	4·4713
10^4m_2	4·3378	4·8485	3·5936	1·9813	2·2535	2·4126	2·5495	1·9679	2·6201
10^4m_3	7·1875	5·7084	5·3596	5·8845	7·5226	8·4511	7·4063	8·0331	9·1779

Expt.	$(E' - E^\circ)$	10^3I	$10^4[H^+]$	$10^4[HC_2O_4^-]$	$10^5[C_2O_4^{2-}]$	$10^4[MC_2O_4]$	$10^{-4}K$
			Temp. = 0°				
4	0·33709	1·723	5·5981	1·6533	2·222	2·7409	5·60
5	0·33243	2·113	5·3863	1·1516	1·638	3·0803	6·26
6	0·33877	2·367	3·6818	0·5814	1·223	2·6342	5·60
8	0·33164	2·251	5·2324	0·9642	1·420	2·9760	6·20
9	0·32831	2·565	5·3095	0·9954	1·463	3·3207	5·95
						Mean $K = 5·92 \pm 0·26$	
			Temp. = 5°				
4	0·34338	1·723	5·5749	1·6768	2·094	2·7303	5·91
6	0·34513	2·369	3·6613	0·6019	1·178	2·6182	5·78
8	0·33791	2·257	5·1932	1·0031	1·378	2·9412	6·30
9	0·33445	2·567	5·2848	1·0201	1·395	3·3029	6·21
						Mean $K = 6·05 \pm 0·21$	

XUM

TABLE 2. (*Continued.*)

Expt.	$(E' - E^\circ)$	10^3I	$10^4[H^+]$	$10^4[HC_2O_4^-]$	$10^5[C_2O_4^{2-}]$	$10^4[MC_2O_4]$	$10^{-4}K$
			Temp. = 15°				
1	0·33477	2·435	10·8014	5·8534	3·946	4·2483	5·62
2	0·35283	1·848	6·4859	3·6266	3·966	3·4573	5·64
3	0·34364	2·003	10·0386	6·0320	4·293	3·3708	5·84
4	0·35568	1·719	5·5921	1·6593	2·091	2·7479	6·03
5	0·35092	2·119	5·3482	1·1892	1·597	3·0465	6·37
7	0·35302	2·075	4·9883	1·1107	1·596	3·0539	6·54
8	0·34995	2·250	5·2243	0·9722	1·344	2·9756	6·61
9	0·34660	2·572	5·2674	1·0370	1·442	3·2811	5·99
						Mean $K = 6·08 \pm 0·32$	
			Temp. = 25°				
1	0·34646	2·425	10·7932	5·8618	3·659	4·2687	6·18
2	0·36519	1·841	6·4688	3·6436	3·695	3·4674	6·13
3	0·35571	1·999	10·0025	6·0680	4·010	3·3630	6·25
4	0·36843	1·733	5·5157	1·7348	2·051	2·6759	5·89
5	0·36331	2·122	5·3168	1·2202	1·526	3·0224	6·62
7	0·36580	2·095	4·8970	1·2010	1·628	2·9599	6·14
8	0·36267	2·273	5·1204	1·0747	1·405	2·8663	6·02
						Mean $K = 6·18 \pm 0·15$	
			Temp. = 35°				
1	0·35842	2·434	10·6757	5·9676	3·339	4·1892	6·52
2	0·37786	1·847	6·3769	3·7309	3·400	3·4072	6·43
3	0·36801	2·007	9·8810	6·1784	3·663	3·2818	6·47
4	0·38115	1·740	5·4489	1·7992	1·909	2·6246	6·16
5	0·37596	2·136	5·2338	1·3010	1·465	2·9466	6·67
7	0·37842	2·102	4·8415	1·2548	1·525	2·9156	6·44
8	0·37509	2·277	5·0795	1·1142	1·301	2·8365	6·45
9	0·37125	2·586	5·1728	1·1294	1·312	3·2005	6·44
						Mean $K = 6·45 \pm 0·08$	
			Temp. = 45°				
1	0·37024	2·432	10·6254	6·0146	3·041	4·1702	7·14
2	0·39050	1·852	6·3028	3·8033	3·155	3·3585	6·74
3	0·38028	2·015	9·7853	6·2705	3·377	3·2164	6·72
4	0·39386	1·746	5·3926	1·8543	1·788	2·5810	6·43
5	0·38838	2·138	5·2032	1·3309	1·356	2·9272	7·18
7	0·39117	2·113	4·7706	1·3246	1·470	2·8507	6·49
8	0·38762	2·285	5·0261	1·1666	1·239	2·7898	6·65
9	0·38352	2·588	5·1428	1·1588	1·219	3·1801	6·93
						Mean $K = 6·79 \pm 0·23$	

Manganese oxalate

Expt.	1	2	3	4	5	6	7
10^3m_1...	3·4320	4·7888	3·0967	2·6820	6·0543	3·8573	4·5292
10^3m_2...	3·2776	4·4524	2·8542	2·7137	3·1920	5·3869	6·1270
10^3m_3...	9·3107	10·5926	8·9826	7·7665	9·0494	8·6069	8·6630

Expt.	$(E' - E^\circ)$	10^2I	$10^3[H^+]$	$10^3[HC_2O_4^-]$	$10^5[C_2O_4^{2-}]$	$10^3[MC_2O_4]$	$10^{-3}K$
			Temp. = 0°				
1	0·24805	2·805	1·9402	1·5637	9·437	1·7327	8·37
2	0·23893	3·233	2·5586	2·4025	11·402	2·1902	8·50
3	0·24977	2·705	1·8609	1·4069	8·773	1·5663	8·17
4	0·25855	2·329	1·4553	1·1485	8·830	1·4220	8·01
5	0·22908	2·962	4·5000	3·9386	10·391	1·7728	8·33
						Mean $K = 8·28 \pm 0·15$	
			Temp. = 15°				
1	0·26232	2·811	1·9043	1·5999	9·320	1·6979	8·53
2	0·25270	3·241	2·5125	2·4497	11·229	2·1453	8·69
3	0·26410	2·711	1·8288	1·4391	8·649	1·5354	8·34
4	0·27318	2·331	1·4400	1·1639	8·556	1·4094	8·41
5	0·24208	2·970	4·4585	3·9828	10·052	1·7333	8·64
6	0·28139	2·530	0·9430	1·3499	15·461	2·3354	8·13
7	0·27745	2·574	1·1004	1·7775	17·523	2·5497	8·11
						Mean $K = 8·41 \pm 0·18$	

XUM

TABLE 2. (*Continued.*)

Expt.	$(E' - E^\circ)$	10^2I	$10^3[H^+]$	$10^3[HC_2O_4^-]$	$10^5[C_2O_4^{2-}]$	$10^3[MC_2O_4]$	$10^{-4}K$
			Temp. = 25°				
1	0·27154	2·808	1·9060	1·5986	8·672	1·7058	0·941
2	0·26152	3·237	2·5218	2·4413	10·396	2·1625	0·969
3	0·27321	2·706	1·8423	1·4261	7·927	1·5559	0·943
4	0·28282	2·329	1·4384	1·1658	7·991	1·4133	0·921
5	0·25066	2·969	4·4532	3·9904	9·402	1·7334	0·944
6	0·29138	2·527	0·9396	1·3536	14·500	2·3415	0·889
7	0·28727	2·570	1·0978	1·7805	16·390	2·5583	0·889
						Mean $K = 0·928 \pm 0·024$	
			Temp. = 35°				
1	0·28101	2·808	1·8905	1·6105	7·864	1·7002	1·06
2	0·27065	3·236	2·5025	2·4539	9·407	2·1565	1·09
3	0·28270	2·705	1·8296	1·4357	7·172	1·5524	1·06
4	0·29271	2·329	1·4240	1·1781	7·276	1·4071	1·03
5	0·25940	2·968	4·4221	4·0024	8·481	1·7210	1·06
6	0·30162	2·524	0·9280	1·3638	13·192	2·3436	1·00
7	0·29735	2·566	1·0852	1·7910	14·879	2·5618	1·00
						Mean $K = 1·04 \pm 0·03$	
			Temp. = 45°				
1	0·29055	2·809	1·8735	1·6268	7·271	1·6894	1·16
2	0·27986	3·237	2·4803	2·4749	8·690	2·1420	1·20
3	0·29222	2·705	1·8179	1·4468	6·596	1·5467	1·18
4	0·30261	2·329	1·4112	1·1905	6·723	1·4000	1·13
5	0·26817	2·971	4·3939	4·0271	7·793	1·7015	1·17
6	0·31194	2·522	0·9157	1·3760	12·226	2·3410	1·10
7	0·30741	2·564	1·0736	1·8024	13·719	2·5619	1·11
						Mean $K = 1·15 \pm 0·03$	

ΔH, ΔC_p, and ΔS calculated from the equations $\Delta H = 2·303\boldsymbol{R}T^2(b + 2cT)$, $\Delta C_p = 4·606\boldsymbol{R}T(b + 3cT)$, and $\Delta S = (\Delta H - \Delta G)/T$, are given in Table 4. The mean deviations have been estimated by using different combinations of experimental points at three temperatures for the calculation of a, b, and c.

The values of ΔC_p may be compared with 35—45 cal. deg.$^{-1}$ for a number of reactions in which hydrogen ion associates with an anion.[9] $\Delta C_p(CoC_2O_4)$ appears to be rather low, but the larger values for NiC_2O_4 and MnC_2O_4 reflect the trend with charge type observed in proton-transfer reactions. A ΔC_p of 70 cal. deg.$^{-1}$ has been found for the association of tervalent chromium with thiocyanate ion.[10]

The entropy of association may be written:

$$\Delta S = \Delta S_g + \Delta S_{hyd}(MC_2O_4) - \Delta S_{hyd}(M^{2+}) - \Delta S_{hyd}(C_2O_4^{2-}) \quad . \quad . \quad (2)$$

where ΔS_g and ΔS_{hyd} are respectively gaseous and hydration entropies. ΔS_g has been calculated as described previously,[11] by using a non-planar model for the complex species with the M–O and oxalate planes at an angle of 101°. $\Delta S_{hyd}(MC_2O_4)$ obtained from

TABLE 3. *Parameters for temperature-dependence of* log K.

	a	-10^2b	10^5c
NiC_2O_4	9·065	2·655	4·512
CoC_2O_4	6·810	1·500	2·760
MnC_2O_4	8·141	3·146	5·857

The calculated K values have a maximum difference of 3% from the observed values.

equation (2) is given in Table 5. The values are lower than the 63—71 cal. deg.$^{-1}$ mole^{-1} observed for the corresponding sulphate ion pairs; this may be due to a greater neutralisation of charge accompanying the formation of oxalate complexes. The change in $\Delta S_{hyd}(MC_2O_4)$ is small but, as far as differences are significant, it varies in the expected

[9] Pitzer, *J. Amer. Chem. Soc.*, 1937, **59**, 2365.
[10] Postmus and King, *J. Phys. Chem.*, 1955, **59**, 1208.
[11] Nair and Nancollas, *J.*, 1958, 3706.

direction with the reciprocal of the cationic radius. The entropy of association increases with temperature and the values at 0° and 45° are respectively; NiC_2O_4, 21·0 and 28·2; CoC_2O_4, 22·0 and 25·8; MnC_2O_4, 18·6 and 27·0 cal. deg.$^{-1}$ mole^{-1}. This increase reflects the greater freedom of the " frozen " solvent molecules when released from the fields of the ions at the higher temperatures.

TABLE 4. *Thermodynamic properties*

Reaction	ΔH (kcal. mole^{-1})	ΔG_{298} (kcal. mole^{-1})	ΔS (cal. deg.$^{-1}$ mole^{-1})	ΔC_p (cal. deg.$^{-1}$)
$Ni^{2+} + C_2O_4^{2-}$	0·15 ± 0·10	−7·05 ± 0·02	24·2 ± 0·4	35 ± 12
$Co^{2+} + C_2O_4^{2-}$	0·59 ± 0·07	−6·54 ± 0·02	23·9 ± 0·3	20 ± 10
$Mn^{2+} + C_2O_4^{2-}$	1·42 ± 0·20	−5·41 ± 0·02	22·9 ± 0·7	65 ± 15

TABLE 5. *Thermodynamic properties*

Ion pair	$S_g(MC_2O_4)$ (cal. deg.$^{-1}$ mole^{-1})	ΔS (cal. deg.$^{-1}$ mole^{-1})	$S°(MC_2O_4)$ (cal. deg.$^{-1}$ mole^{-1})	$-\Delta S_{hyd}(MC_2O_4)$ (cal. deg.$^{-1}$ mole^{-1})	r_+^{-1} (Å^{-1})
NiC_2O_4.....	70·0	24·7	13·9	56·1	1·37
CoC_2O_4	70·0	23·9	14·1	55·8	1·35
MnC_2O_4	69·9	22·9	15·1	54·8	1·28

The heat changes, ΔH, oppose the association reactions and it is these terms which account for the considerable differences of stability over the series of cations. This is to be expected for transition-metal ion complexes, and it has also been claimed that equations of the form

$$\Delta H = Az/r_+ + BI_{02} - C/r_+^3$$

may be used to represent the data.[12] The ΔH values of Table 4 follow the reverse of this order, decreasing with increasing r_+^{-1} and ionization potential I_{02}. When ΔH is expressed by an equation analogous to (2), and all other terms are assumed to be approximately constant, ΔH should increase with $-\Delta H_{hyd}(M^{2+})$; the opposite order is observed: more results are required to explain this.

We thank Dr. H. S. Dunsmore for advice on computer programmes, and the D.S.I.R. for a grant to A. McA.

THE UNIVERSITY, GLASGOW, W.2. [*Received, November 7th,* 1960.]

[12] Williams, *J. Phys. Chem.*, 1954, **58**, 121.

---

421. *The Transmission of Polar Effects through Aromatic Systems. Part I. Substituted Anthracenes.*

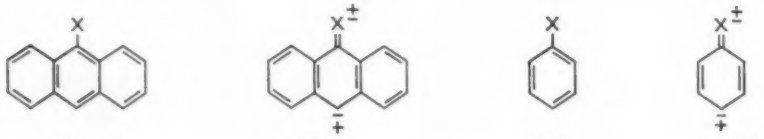
By R. O. C. NORMAN and P. D. RALPH.

The effects of substituents in the 10-position of the anthracene nucleus on the acid strengths of 9-anthroic acids and on the stretching frequencies of the carbonyl bonds in the corresponding methyl esters have been determined. The results show that the carbonyl group in the acids and esters is precluded from resonance interaction with the aromatic ring, as is a nitro-group at position 10. This conclusion is supported by the results of measurements of the CN stretching frequencies in certain aromatic nitriles, and evidence is also adduced from these measurements that a substituent capable of mesomeric interaction interacts more strongly when bonded to a *meso*-carbon in anthracene than when bonded to a benzenoid carbon atom.

IN anthracene, both the atom localisation energy of a *meso*-carbon atom and the *para*-localisation energy of the central ring have smaller values than in benzene.[1] These

[1] Wheland, *J. Amer. Chem. Soc.*, 1942, **64**, 900.

differences arise since the resonance energy of anthracene is less than three times the resonance energy of benzene, so that, for example, less resonance energy is lost when anthracene is reduced to the 9,10-dihydro-compound than when benzene is reduced to cyclohexa-1,4-diene. For the same reason, the difference in energies between structures (I) and (II) should be smaller than that between (III) and (IV). Thus, (II) should be a relatively more important canonical form in the resonance hybrid of the 9-substituted anthracene than is (IV) in the corresponding benzenoid hybrid. If X is a substituent capable of mesomeric interaction, its *mesomeric* effect should be greater, if the above is true, when it is attached to the central ring in anthracene than when it is bonded to benzene.



(I) (II) (III) (IV)

It was therefore of interest to examine the polar effects of groups attached to a *meso*-position of anthracene on the properties of a functional centre at the other *meso*-position, and to compare these effects with those in benzenoid compounds.

The anthracene nucleus also provides a convenient system for an investigation of the effects of the steric inhibition of resonance. A substituent in a *meso*-position is subject to repulsive forces from two *peri*-hydrogen atoms, and, if it lacks spherical or cylindrical symmetry, can as a result be twisted from coplanarity with the ring. For example, it is known that the nitro-group in 9-nitroanthracene is twisted through an angle of 85° in the solid.[2] Such non-coplanarity should result in reduced π-orbital overlap between the substituent and the nucleus which in turn should alter the polar effect of the substituent on the aromatic nucleus. Conversely, by investigating the polar effect of such a substituent on the properties of a functional group at some other position in the molecule, evidence concerning the steric inhibition of resonance can be obtained.

Three techniques were chosen for these studies: measurement of the acid-dissociation constants of 10-substituted 9-anthroic acids; of the carbonyl stretching frequencies of 10-substituted-9-anthroates; and of the rates of alkaline hydrolysis of the same esters.

Discussion

Preparation of Materials.—Most of the compounds were known and were prepared by methods reported in the literature. Methyl 10-nitro-9-anthroate was prepared by nitration of methyl 9-anthroate with concentrated nitric acid in boiling acetic acid, attempts to carry out the reaction at lower temperatures being unsuccessful. The position taken up by the nitro-group was confirmed by oxidation of the compound to anthraquinone. The corresponding acid was obtained by vigorous alkaline hydrolysis of the ester. Attempts to make methyl 10-cyano-9-anthroate were unsuccessful. Treatment of methyl 10-bromo-9-anthroate with cuprous cyanide in refluxing quinoline resulted not only in the displacement of bromide by cyanide but also in the removal of the methoxycarbonyl-group, presumably by attack of cyanide ion on the methyl group in an S_N2 reaction to give the corresponding carboxylate ion which should decarboxylate readily.[3] When the lower-boiling solvents, 2,4,6-collidine and dimethylformamide, were used 9-anthronitrile was again obtained, together, in the latter solvent, with some starting material. It did not appear possible to carry out the reaction so that only the bromide was displaced, and attempts to make

[2] Trotter, *Canad. J. Chem.*, 1959, **37**, 351.
[3] Schenkel, *Helv. Chim. Acta*, 1946, **29**, 436.

the cyano-ester were discontinued. On the other hand, 9,10-dicyanoanthracene (required for infrared measurements) was prepared from 10-bromo-9-anthronitrile by displacement with cuprous cyanide in boiling quinoline. 10-Bromo-9-anthronitrile was itself prepared by uncatalysed bromination of the 9-nitrile in boiling nitromethane, and its structure was confirmed by its oxidation to anthraquinone.

pK_A *Values of* 9-*Anthroic Acids*.—The strengths of the 10-substituted-9-anthroic acids in 80% " Methylcellosolve " at 25° (Table) were measured by Dr. W. Simon at Eidgenössische Technische Hochschule, Zurich. The pK_A values were plotted against both the Hammett σ values derived by Jaffé [4] and the σ_n values derived by van Bekkum, Verkade,

Acid	pK_A value	σ_n value	Derived σ value
9-Anthroic acid	5·59	0	0
10-Bromo-9-anthroic acid	5·00	0·265	0·324
10-Chloro-9-anthroic acid	5·03	0·238	0·307
10-Nitro-9-anthroic acid	4·40	(σ_I) 0·630	0·653
10-Methyl-9-anthroic acid	5·71	−0·129	−0·066

and Wepster,[5] both sets of chosen values being those applicable to *para*-substituents. In each case the point corresponding to the nitro-group lay on the best straight line only when the σ-value assumed for it was Taft's (inductive) σ_I value,[6] and, with this value included, the best straight lines were drawn by the method of least squares. The better linear graph was obtained when σ_n values were employed. More specifically, when new σ values for the substituents were derived from the graphs, the mean deviation of the new values from those used to obtain the graphs was 0·08 σ-unit when Hammett σ values were employed, but only 0·045 σ-unit relative to σ_n values. The derived σ values from this graph are also shown in the Table, and the mean deviation (0·045) falls within Taft's limits [7] in respect of the criterion which he has suggested should be applied to any new set of σ values. σ_n Values being used, the ρ value for the ionization reaction was found to be 1·82.

The σ_n value of a group is the Hammett constant appropriate when resonance interaction between the group and the functional centre is precluded,[5] and we therefore conclude that such interaction is prevented in the present case because the carbonyl group of the acid is sterically inhibited from the coplanarity required for such interaction. This conclusion is also consistent with the fact that the σ_I value for the nitro-group is appropriate in this case; evidently the nitro-group is unable to exert its mesomeric effect because it is not coplanar with the ring. Our derived σ value, 0·65, for the nitro-group is only slightly greater than Taft's σ_I value of 0·63, suggesting that resonance interaction is close to zero. This substantiates Trotter's conclusion that there is a considerable angle of twist between the plane of the nitro-group and that of the anthracene nucleus.[2] It is also notable that the σ value of 0·72 obtained for a nitro-group in the 4-position of naphthalene,[8] where only one *peri*-hydrogen atom is present to hinder coplanarity, is about half way between our value and the σ_n value, 0·78,[5] for the nitro-group. Finally, our conclusion that the carbonyl group is not coplanar with the aromatic nucleus is in accord with the fact that anthroic acid, like 2,6-dimethylbenzoic acid, is stronger than benzoic acid itself,[9] Taft having computed that conjugation of the carbonyl group with the benzene nucleus in benzoic acid stabilises the acid relative to its anion by about 1 kcal. mole.$^{-1}$, thereby producing an acid-weakening effect.[10]

[4] Jaffé, *Chem. Rev.*, 1953, **53**, 191.
[5] van Bekkum, Verkade, and Wepster, *Rec. Trav. chim.*, 1959, **78**, 815.
[6] Taft, *J. Phys. Chem.*, 1960, **64**, 1805.
[7] Taft and Lewis, *Tetrahedron*, 1959, **5**, 210.
[8] Fischer, Fountain, and Vaughan, *J.*, 1959, 1310.
[9] Lauer, *Ber.*, 1937, **70**, 1288.
[10] Taft, in Newman, " Steric Effects in Organic Chemistry," Wiley, New York, 1956, pp. 580, 581.

XUM

There is no evidence from the acid strengths that there is an enhancement of the mesomeric effect of a group attached to a *meso*-position in anthracene. Of the compounds studied, only the chloro- and bromo-compounds might have provided such evidence, for the nitro-group is apparently unable to exert its mesomeric effect in this system, while the polar effect of a methyl group is in any case small. Positive evidence would have required that the chloro- and bromo-acids were either weaker than the unsubstituted acid (if the enhanced mesomeric effect were to outweigh the inductive effect), or at least were weaker than the values predicted from a consideration of their σ_n values and the strengths of the other acids. Neither of these requirements was fulfilled. It is therefore reasonable to assume that the chloro- and bromo-substituents are here exerting their normal electron-attracting effects.

Carbonyl and Nitrile Stretching Frequencies.—The carbonyl stretching frequencies (in cm.$^{-1}$) of the substituted methyl anthroates were measured both in carbon tetrachloride and in chloroform on a Unicam S.P. 100 instrument, and are as follows (values in carbon tetrachloride reported first): methyl anthroate, 1734, 1722·5; methyl 10-bromo-9-anthroate, 1734, 1726; methyl 10-chloro-9-anthroate, 1734, 1724; methyl 10-nitro-9-anthroate, 1735, 1728; methyl 10-methyl-9-anthroate, 1730, 1719·5. The lower frequencies observed on changing from carbon tetrachloride to chloroform agree with similar observations by Thompson, Needham, and Jameson.[11]

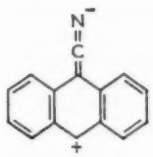
The variation of the carbonyl frequency in carbon tetrachloride is small and irregular, but in chloroform a regular variation of the group frequency with the polar character of the substituent is apparent. The frequency values are accurate and reproducible to ± 1 cm.$^{-1}$ but the range of frequencies is only 8·5 cm.$^{-1}$. Within the limitations of precision implied by this, the results obtained correlate satisfactorily with the pK_A values. Similarly, a graph of the frequencies against σ_n values is linear, though again only when the nitro-group is given Taft's σ_I value. The mean deviation of the points from the best straight line is 0·76 cm.$^{-1}$, and the line has a gradient of 8·9 cm.$^{-1}$ per unit of σ.

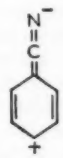
The satisfactory correlation obtained by using the σ_I value for the nitro-group further points to the fact that this group is sterically inhibited from resonance interaction with the aromatic ring, but to obtain further evidence that the carbonyl group is so inhibited another approach was employed. Measurements were made of the stretching frequencies of the carbonyl bond in methyl benzoate and methyl mesitoate, and of the cyano-bond in a series of nitriles, again in carbon tetrachloride and chloroform. The results are: methyl benzoate, 1729, 1718; methyl mesitoate, 1732, 1723; benzonitrile, 2229, 2228·5; *p*-bromobenzonitrile, 2231, 2231; mesitonitrile, 2217·5, 2217; 9-anthronitrile, 2217, 2216; 10-bromo-9-anthronitrile, 2217, 2217; 9,10-dicyanoanthracene, insoluble, 2222·5. The cyano-group, having cylindrical symmetry, cannot be inhibited from resonance interaction with the aromatic nucleus. The CN stretching frequencies of mesitonitrile and 9-anthronitrile are, to within 1 cm.$^{-1}$, the same, and about 12 cm.$^{-1}$ lower than that of benzonitrile. The CN bonds in the first two compounds therefore have less triple-bond character than that in benzonitrile, which is diagnostic of the release of electrons to the cyano-group. That is, the 2,3:5,6-dibenzo-substituent (in 9-anthronitrile) behaves as an electron-releasing substituent to the same extent as the 2,4,6-trimethyl grouping in mesitonitrile. Hence, the anthracene nucleus is electron-releasing relative to benzene; structure (V) is relatively more important in 9-anthronitrile than is (VI) in benzonitrile. On the other hand, methyl mesitoate and methyl 9-anthroate both absorb at higher frequencies than methyl benzoate. Yet, from consideration of polar factors, the shift in carbonyl frequencies should be in the same direction (to lower frequency) as in the corresponding nitriles. The conclusion is that inhibition of resonance is sufficient in each case to cause a shift in the opposite direction from that predicted by the electron-releasing natures of the 2,3:5,6-dibenzo- and 2,4,6-trimethyl groupings, this restriction of conjugation

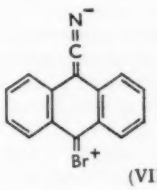
[11] Thompson, Needham, and Jameson, *Spectrochim. Acta*, 1957, **9**, 208.

giving the carbonyl bonds higher double-bond character than that in their unsubstituted analogue.

The relatively larger contribution of structure (V) than of structure (VI) to the respective hybrids is the first evidence from these results in accord with the theory that substituents capable of mesomeric interaction should interact more strongly when bonded at the *meso*-position of anthracene than when substituted in benzene. Confirmation of this was obtained from measurements of the stretching frequencies of the CN bonds in *p*-bromobenzonitrile and 10-bromo-9-anthronitrile. The shift to lower frequencies (2 and 2·5 cm.$^{-1}$ in carbon tetrachloride and chloroform, respectively) brought about by the *p*-bromo-substituent in *p*-bromobenzonitrile is consistent with electron-withdrawal by the bromine atom. The shift to lower frequencies on introduction of the 10-bromo-substituent into 9-anthronitrile is markedly less (0 and 1 cm.$^{-1}$ in carbon tetrachloride and chloroform, respectively). The 10-bromo-group appears to have a very small, perhaps negligible, electron-withdrawing effect, consistent with an enhanced mesomeric effect counterbalancing its inductive effect. Evidently structure (VII) is a relatively more important canonical structure than the corresponding structure in *p*-bromobenzonitrile.


(V)


(VI)


(VII)

It has to be explained why the bromo-substituent shows an enhanced mesomeric effect in 10-bromo-9-anthronitrile but not in the corresponding ester. In the nitrile this effect appears to be due to conjugation between the bromine and the cyano-group, nitrogen being a stable sink for negative charge [see structure (VII)]. In the ester the corresponding structure is sterically precluded. There should be no conjugation between the two cyano-groups in 9,10-dicyanoanthracene, so that the shift to higher frequencies on introduction of the 10-cyano-substituent into 9-anthronitrile should be about the same as that on introduction of a *p*-cyano-substituent into benzonitrile. We measured the CN stretching frequency of 9,10-dicyanoanthracene in chloroform solution (the dicyanide was insoluble in carbon tetrachloride) and found it to be 5·5 cm.$^{-1}$ higher than that of 9-anthronitrile (see p. 2224); the corresponding difference between the benzene analogues in chloroform solution is reported[12] to be 7 cm.$^{-1}$ (9,10-Dicyanoanthracene has a second, weak, CN band because of vibrational coupling.)

Hydrolysis of Anthroic Esters.—The bimolecular rate constant for the alkaline hydrolysis of ethyl 9-anthroate has been reported.[13] We found that the corresponding methyl ester and methyl 10-bromo-9-anthroate could not be hydrolysed under the same conditions, even though methyl esters are hydrolysed faster than their ethyl analogues.[14] A slow decrease in base concentration was observed, but a blank experiment showed that this was due to uptake of base by the glass vessel. In any case the rate of loss of base was slower by at least a factor of 4 than that expected for a reaction having a rate constant equal to or greater than the value reported for ethyl 9-anthroate. We concluded that alkaline hydrolysis of anthroic esters, like that of mesitoic esters,[15] is subject to a powerful steric retardation.

[12] Krueger and Thompson, *Proc. Roy. Soc.*, 1959, *A*, **250**, 22.
[13] Adam-Briers, Fierers, and Martin, *Helv. Chim. Acta*, 1955, **38**, 2021.
[14] Gore, Vignes, and Feinstein, *Chem. and Ind.*, 1958, 1514.
[15] Goering, Rubin, and Newman, *J. Amer. Chem. Soc.*, 1954, **76**, 787.

XUM

We discovered that anthroic esters are also similar to other hindered esters [16] in that they can be hydrolysed to the corresponding acids by dissolution in concentrated sulphuric acid followed by pouring into water. This procedure was successful for all the methyl esters we prepared save the 10-nitro-compound; and it was possible to hydrolyse this ester under alkaline conditions of extreme vigour.

Experimental

M. p.s were taken on a micro-Kofler block and are corrected. Alumina was P. Spence and Sons, Ltd., Type " H." Light petroleum had b. p. 60—80°.

Methyl 9-anthroate,[17] 10-bromo-9-anthroate,[18] 10-chloro-9-anthroate,[18] and 10-methyl-9-anthroate [18] were prepared from the acids by using diazomethane and were purified by chromatography on alumina followed by recrystallisation from light petroleum. Methyl 9-anthroate had m. p. 115° (lit.,[19] 112·1—113·2°) (Found: C, 81·6; H, 5·1. Calc. for $C_{16}H_{12}O_2$: C, 81·3; H, 5·0%). Methyl 10-bromo-9-anthroate had m. p. 114° (lit.,[20] 114—115°), methyl 10-chloro-9-anthroate had m. p. 123° (lit.,[21] 123°), and *methyl 10-methyl-9-anthroate* had m. p. 164° (Found: C, 81·3; H, 6·1. $C_{17}H_{14}O_2$ requires C, 81·6; H, 5·6%).

Methyl 10-Nitro-9-anthroate.—A solution of methyl 9-anthroate (5·6 g.) and concentrated nitric acid (1·4 ml.) in glacial acetic acid (260 ml.) was boiled for 20 min. and poured into water. The ethereal extract was washed, dried (Na_2SO_4), and distilled. The residue was taken up in light petroleum and filtered through alumina; further purification by repeated recrystallisation from light petroleum and ethanol gave yellow needles (0·29 g., 4%), m. p. 171—171·5°, which were shown to be *methyl 10-nitro-9-anthroate* (Found: C, 68·7; H, 4·0; N, 5·0. $C_{16}H_{11}NO_4$ requires C, 68·2; H, 3·9; N, 5·0%) as follows: The infrared spectrum showed bands characteristic of the ester (1720 cm.$^{-1}$) and nitro (1530 and 1360 cm.$^{-1}$) groupings, while the ultraviolet spectrum showed the bands characteristic of anthracenes ($\lambda_{max.}$ = 2520 and 3610 Å). The ester (23 mg.) was oxidised to anthraquinone by potassium dichromate (0·5 g.) and concentrated sulphuric acid (2 ml.) in 95% acetic acid (8 ml.) at 100° for 30 min. The solution was poured into water and extracted with chloroform followed by washing, drying ($CaCl_2$), and evaporation of the solvent; material was obtained identified as anthraquinone (m. p. 274—278°; infrared spectrum identical with that of an authentic sample).

Attempts to prepare Methyl 10-Cyano-9-anthroate.—A typical experiment was as follows. Methyl 10-bromo-9-anthroate (0·5 g.) was dissolved in dimethylformamide (20 ml.), cuprous cyanide (1 g.) was added, and the solution, after being boiled for 20 min., was poured whilst hot into excess of dilute aqueous ammonia. A benzene extract was washed and evaporated; recrystallisation of the residue from light petroleum gave 9-anthronitrile (0·15 g.), m. p. 177—178° (no depression with an authentic sample) (Found: C, 88·8; H, 4·7; N, 6·4. Calc. for $C_{15}H_9N$: C, 88·7; H, 4·5; N, 6·9%). Evaporation of the mother liquor and recrystallisation from light petroleum gave starting material (0·20 g.), m. p. 112—113°. Similar experiments were performed with quinoline and 2,4,6-collidine as solvents. In each case a small yield (about 15%) of 9-anthronitrile was the only isolable product.

10-Substituted 9-Anthroic Acids.—Newman's hydrolytic method [16] was successful with all the methyl esters except methyl 10-nitro-9-anthroate. The acids were recrystallised from ethanol.

Compound	Crystal form	Yield (%)	M. p.	Lit. m. p.
9-Anthroic acid	Needles	63	219°	218—219° [16]
10-Bromo-9-anthroic acid	Needles	66	285	265—267; [18] 273 [20]
10-Chloro-9-anthroic acid.....	Needles	55	275—276	268·5—269·5 [18]
10-Methyl-9-anthroic acid	Plates	66	220	219—220 [18]

10-Nitro-9-anthroic acid.—Methyl 10-nitro-9-anthroate (0·24 g.) and sodium hydroxide (3·5 g.) in 85% ethanol (300 ml.) were boiled for 24 hr. (by which time reaction was not completed), and the solution was poured into water, the mixture filtered, and the filtrate acidified,

[16] Newman, *J. Amer. Chem. Soc.*, 1941, **63**, 2431.
[17] Mikhailov, *Izvest. Akad. Nauk S.S.S.R., Otdel. khim. Nauk*, 1948, 420.
[18] Mikhailov and Bronovitskaya, *Zhur. obshchei Khim.*, 1952, **22**, 157.
[19] Bartlett and Greene, *J. Amer. Chem. Soc.*, 1954, **76**, 1088.
[20] Beyer and Fritsch, *Ber.*, 1941, **74**, 494.
[21] Behla, *Ber.*, 1887, **20**, 701.

XUM

to give 10-*nitro*-9-*anthroic acid* (0·1 g.; 43%), m. p. 275° (from ethanol) (Found: C, 67·3; H, 3·4; N, 4·6. $C_{15}H_9NO_4$ requires C, 67·5; H, 3·4; N, 5·2%).

Methyl benzoate had b. p. 197°/749 mm.; benzonitrile had b. p. 191°/762 mm.; *p*-bromobenzonitrile [22] had m. p. 112° (lit.,[22] 113°); mesitonitrile [23] had m. p. 55°; and methyl mesitoate [16,24] had b. p. 98°/3 mm. 9-Anthronitrile [25] had m. p. 177·5—178·5° (lit.,[25] 177·5—179°).

10-*Bromo*-9-*anthronitrile*.—A solution of 9-anthronitrile (0·88 g.) and bromine (0·68 g.) in nitromethane (30 ml.) was boiled for 20 min. The material deposited on cooling was recrystallised from toluene, giving 10-*bromo*-9-*anthronitrile* (0·63 g.; 53%) which has m. p. 193°, resolidifies on further heating, and melts again at 265° (Found: C, 63·5; H, 2·8; N, 4·8; Br, 27·7. $C_{15}H_8BrN$ requires C, 63·8; H, 2·9; N, 4·9; Br, 28·4%). Oxidation to anthraquinone was brought about under the same conditions as those used for methyl 10-nitro-9-anthroate. The product had m. p. 281° and an infrared spectrum identical with that of an authentic sample of anthraquinone.

9,10-*Dicyanoanthracene* (cf. ref. 20).—10-Bromo-9-anthronitrile (0·24 g.) and cuprous cyanide (0·5 g.) were dissolved in quinoline (30 ml.) and the solution was boiled for 1 hr. The product was isolated in the usual way and purified by filtration through alumina in benzene solution, to give 9,10-dicyanoanthracene (0·12 g.; 62%), m. p. 334° (from benzene) (lit.,[20] 328—330°).

pK_A-*Measurements*.—Measurements were made in a microtitration apparatus at 25°, solutions of the acids being used in 80% " Methylcellosolve."

Spectrophotometric Measurements.—A Unicam S.P. 100 spectrophotometer, fitted with a prism grating monochromator, was employed. Under the conditions used, the spectral slit-width was probably about 5 $cm.^{-1}$. Materials were examined in dilute solution in carbon tetrachloride (" AnalaR "; B.D.H.) and chloroform (May and Baker, Ltd.). The container was a sodium chloride cell of 1 mm. path-length.

Hydrolysis Measurements.—The procedures for standardisation of solutions and attempted kinetic measurements were essentially those of Evans, Gordon, and Watson.[26] The solvent used, 85% ethanol, was made up by appropriate dilution, with boiled-out distilled water, of ethanol, purified by the method of Lund and Bjerrum.[27] Kinetic measurements were carried out at 70°, with use of a reaction vessel with a ground-glass stopper which was fitted with springs to minimise solvent evaporation. Samples were withdrawn at intervals during 24 hr. and titrated. The initial sodium hydroxide concentration(M/20) had decreased to M/40 in between 20 and 24 hr., but this decrease was independent of the presence of ester. It most nearly obeyed zero-order kinetics.

We thank Dr. W. Simon for measuring the dissociation constants of the anthroic acids.

THE DYSON PERRINS LABORATORY, OXFORD UNIVERSITY. [*Received, November 25th*, 1960.]

[22] Zappi, and Deferrari, *Anales Asoc. quím. argentina*, 1946, **34**, 146.
[23] Fuson and Denton, *J. Amer. Chem. Soc.*, 1941, **63**, 654.
[24] *Org. Synth.*, Coll. Vol. III, 1955, 553.
[25] Fieser and Hartwell, *J. Amer. Chem. Soc.*, 1938, **60**, 2555.
[26] Evans, Gordon, and Watson, *J.*, 1937, 1430.
[27] Vogel, " Textbook of Practical Organic Chemistry," Longmans, 1951, p. 167.

XUM

422. *The Resolution of Chlorpheniramine and Pheniramine.*

By J. H. Hunt.

The resolution of the antihistaminic drugs chlorpheniramine and pheniramine with optically active di-*p*-toluoyltartaric acids is described. It has also been found that from solutions of salts of the inactive bases with an inactive acid (3,5-dinitrobenzoic acid), seeding causes preferential crystallisation of the salts of the active bases. From this observation, a method for resolving large amounts of chlorpheniramine has been developed.

Some of the differences in pharmacological properties of the optical isomers of chlorpheniramine, (3-*p*-chlorophenyl-*NN*-dimethyl-3-2′-pyridylpropylamine), a potent antihistaminic drug,[1] were first reported by Roth and Govier [2] who used bases resolved with active phenylsuccinic acids. The details of this resolution have only recently appeared.[3] In the meantime, a communication from these laboratories reporting the pharmacological properties of the active isomers included a preliminary note on the resolution of (±)-chlorpheniramine with active di-*p*-toluoyltartaric acids and gave the physical constants of the active bases.[4]

Details of this method are now reported. It has been improved by the substitution of hydrochloric acid for half an equivalent of the active acid,[5] resulting in easier crystallisation and a cleaner separation of the less soluble diastereoisomeric salt. 30% Aqueous ethanol is the best solvent found, and when crystallisation has commenced it is important to allow the solution to cool very slowly to avoid separation of the salt in a sticky form of low optical purity.

To avoid confusion, the term (+−)-salt will be used here to describe the salt of the dextrorotatory base with the lævorotatory acid derived from (+)-tartaric acid.

At first, the two enantiomorphs of chlorpheniramine were obtained by the use of the (+)- and the (−)-acid respectively. However, since the (−)-acid is more readily available, it was desirable to find a salt of a simple acid which could be used to separate active from inactive base in partially resolved mixtures obtained from the mother-liquors after the (±)-salt had crystallised. Most salts of (±)-chlorpheniramine do not crystallise easily or well, but since the salt of the (±)-base with 3,5-dinitrobenzoic acid had already been made in these laboratories and was found to crystallise well, this acid was an obvious choice.

The 3,5-dinitrobenzoates of the active bases were found to be only about half as soluble as the inactive salt and by conversion of the total base in a partially resolved mixture into dinitrobenzoate, the salt of the active base could be recovered optically pure in very high yield.

On one occasion the mother-liquors remaining after the removal of excess of (−)-base from such a mixture were found to be slightly dextrorotatory, indicating that preferential crystallisation of a small amount of the salt of the (−)-isomer in the racemic base had occurred in addition to the separation of the salt of the free (−)-base in the mixture. It was then found that if an acetone solution of the dinitrobenzoate of the inactive base was seeded with active dinitrobenzoate, resolution occurred and gave 9% of that isomer in the inactive mixture as salt of 60% optical purity. This resolution by seeding is not limited to solutions in acetone: it also occurs in ethyl methyl ketone, methanol, propan-2-ol, ethyl acetate, and isopropyl acetate, but no resolution has been observed in benzene, ethylene dichloride, and other non-polar solvents.

If a solution of dinitrobenzoate already containing an excess of one enantiomorph is

[1] Sperber, Papa, Schwenk, Sherlock, and Fricano, *J. Amer. Chem. Soc.*, 1951, **73**, 5752.
[2] Roth and Govier, *J. Pharmacol.*, 1958, **124**, 347.
[3] B.P. 834,984.
[4] Brittain, D'Arcy, and Hunt, *Nature*, 1959, **183**, 734.
[5] Pope and Peachey, *J.*, 1899, **75**, 1066.

seeded, the amount of base resolved is increased, the increase depending to some extent on the amount of the excess. For a given concentration in a given solvent it is possible within limits to choose an excess of active base such that the first crop of dinitrobenzoate contains in addition to the salt of the excess active base an equal quantity of salt of th same enantiomorph from the inactive base. An equal amount of the other enantiomorph is left in the mother-liquor from which, after replenishment with more inactive salt, a second crop of dinitrobenzoate is obtained equal to the first but of opposite rotation. This procedure can be repeated indefinitely and provides a very successful process for resolving large quantities of (±)-chlorpheniramine. One experimental run was continued for three months during which more than 50 crops [alternately of (+)- and (−)-salt] were collected with no significant falling off in quantity or quality of the product.*

An initial excess of (+)- or (−)-base equal to 15% of the inactive base (*i.e.*, a 30% excess of that enantiomorph) has been found to be satisfactory, and ethyl methyl ketone is the best solvent found, giving least variation in amount and optical purity of successive crops of salt. It is also an advantage to limit the amount of dinitrobenzoic acid to that required to combine with the total amount of the isomer which is in excess; acetic acid may be added to complete the neutralisation but with no advantage.

The salt thus obtained, of average optical purity 85%, gives, after one recrystallisation from acetone, dinitrobenzoate of 98% optical purity in excellent yield. The factors which favour the resolution also operate in this recrystallisation.

The melting-point curve for mixtures of (+)- and (−)-chlorpheniramine dinitrobenzoates has been determined. It is of normal two-component type with one eutectic corresponding to the composition of the inactive salt, and indicates that the latter is a racemic mixture. The success of the resolution is doubtless partly due to this and also to the extreme stability of supersaturated solutions of the inactive dinitrobenzoate. A solution in acetone containing four times the amount for saturation failed to crystallise during three weeks at room temperature.

The preparation of (+)-pheniramine (*NN*-dimethyl-3-phenyl-3-2′-pyridylpropylamine) by catalytic dehalogenation of (+)-chlorpheniramine appeared in a recent patent [3] in which the resolution of (±)-pheniramine by (+)-phenylsuccinic and (+)-*p*-nitrophenylsuccinic acid is inferred although no optical constants are quoted for the base so prepared.

In the present study, (±)-pheniramine could only be partially resolved with (−)-*OO*-di-*p*-toluoyltartaric acid,† giving a base with $[\alpha]_D$ −8°. However, by repeated crystallisation of the 3,5-dinitrobenzoate of the partially resolved base, the (−)-base was obtained with $[\alpha]_D$ −36·3°. The (+)-base was obtained with $[\alpha]_D$ +37·5° in a similar way from the di-*p*-toluoyltartrate mother-liquors.

By its preparation from (+)-chlorpheniramine, (+)-pheniramine has by inference the same configuration; also in both compounds the (+)-forms have the higher antihistaminic activity. It is interesting therefore that whereas with chlorpheniramine it is the (+)-base which gives the less soluble diastereoisomeric salt with the (−)-acid, with pheniramine it is the (−)-base.

It has been found that, as with chlorpheniramine, solutions of pheniramine 3,5-dinitrobenzoate can be resolved by seeding with a crystal of an active form; also that a similar semi-continuous method of resolution can be applied, although from a limited number of experiments it appears that the method is not so satisfactory as with chlorpheniramine. This is probably due to the lesser tendency of (±)-pheniramine 3,5-dinitrobenzoate to form stable supersaturated solutions. As a result, the salt which separates

* A somewhat similar method of working has been used for " seeding " resolutions of (±)-threonine and (±)-*threo*-2-amino-1-*p*-nitrophenylpropane-1,3-diol.[4]

† It is regretted that in an earlier paper (*J.*, 1957, 1926) dextrorotatory *OO*-di-*p*-toluoyltartaric acid, referred to in the manuscript as di-*p*-toluoyl-L-tartaric acid, was changed editorially to (−)-*OO*-di-*p*-toluoyltartaric acid.

[4] B.P. 740,319, 756,042.

XUM

is of lower optical purity and is also more difficult to purify, requiring six or seven recrystallisations.

The 3,5-dinitrobenzoates of chlorpheniramine and pheniramine can be added to the few examples of inactive substances which can be resolved by preferential crystallisation of either enantiomorph.[6,7]

Experimental

Rotations were determined in a 4 dm. tube.

Resolution of Chlorpheniramine by OO-*Di*-p-*toluoyltartaric Acids*.—(±)-3-*p*-Chlorphenyl-*NN*-dimethyl-3-2′-pyridylpropylamine (24 g.) and (−)-*OO*-di-*p*-toluoyltartaric acid [8] (16·7 g., 0·5 mol.) were dissolved in warm ethanol (60 ml.), and water (80 ml.) containing N-hydrochloric acid (43·1 ml., 0·5 mol.) was added. The solution was cooled slowly until clouding commenced, held at that temperature and scratched until crystallisation began, then allowed to cool overnight to room temperature. The crystals were filtered off, washed with 30% aqueous ethanol (50 ml.), and dried. Two recrystallisations from 50% aqueous ethanol gave (+−)-3-p-*chlorophenyl*-NN-*dimethyl*-3-2′-*pyridylpropylamine* OO-*di*-p-*toluoyltartrate monohydrate*, m. p. 135—136° (needles), $[\alpha]_D^{20}$ −57·8° (*c* 1·7 in EtOH) (Found: C, 64·0; H, 5·9; Cl, 5·0; N, 4·0. $C_{36}H_{37}ClN_2O_8,H_2O$ requires C, 63·7; H, 5·8; Cl, 5·2; N, 4·1%). The anhydrous salt obtained on drying at 60° was very hygroscopic, reverting to the hydrate after a few hours' exposure to air.

The above salt (14 g.) was suspended in water (50 ml.) and basified with N-sodium hydroxide (50 ml.). An ethereal extract of the base was dried (KOH) and evaporated and the residual oil was distilled, giving (+)-3-*p*-chlorophenyl-*NN*-dimethyl-3-2′-pyridylpropylamine, b. p. 120°/0·1 mm., n_D^{20} 1·5608, $[\alpha]_D^{21·5}$ +31·6° (*c* 1·8 in EtOH) (Found: C, 70·0; H, 7·1; Cl, 12·75; N, 10·1. Calc. for $C_{16}H_{19}ClN_2$: C, 69·9; H, 7·0; Cl, 12·9; N, 10·2%). The hydrogen maleate was prepared by adding a solution of maleic acid (1·65 g.) in isopropyl acetate (30 ml.) to a solution of the above base (3·9 g.) in isopropyl acetate (10 ml.). The salt, which crystallised on cooling, recrystallised from isopropyl acetate and then had m. p. 113—114°, $[\alpha]_D^{24}$ +23·1° (*c* 1·2 in H_2O) (Found: C, 61·4; H, 6·0; Cl, 9·3; N, 6·7. Calc. for $C_{20}H_{23}ClN_2O_4$: C, 61·4; H, 5·9; Cl, 9·1; N, 7·2%).

In a similar way, (±)-base and (+)-*OO*-di-*p*-toluoyltartaric acid [9] gave (−+)-3-p-*chlorophenyl*-NN-*dimethyl*-3-2′-*pyridylpropylamine* OO-*di*-p-*toluoyltartrate monohydrate*, m. p. 135°, $[\alpha]_D^{24}$ +57·4° (*c* 1·1 in EtOH) (Found: C, 64·3; H, 5·9; Cl, 5·7; N, 4·7%). By basifying the salt, (−)-3-*p*-chlorophenyl-*NN*-dimethyl-3-2′-pyridylpropylamine was obtained, with b. p. 121°/0·1 mm., n_D^{19} 1·5609, $[\alpha]_D^{21·5}$ −31·6° (*c* 1·8 in EtOH) (Found: C, 70·3; H, 7·1; Cl, 12·4; N, 9·9%). The hydrogen maleate had m. p. 114—115°, $[\alpha]_D^{25}$ −23·1° (*c* 1·2 in H_2O) (Found: C, 61·1; H, 5·8; Cl, 9·2; N, 7·4%).

(±)-3-p-*Chlorophenyl*-NN-*dimethyl*-3-2′-*pyridylpropylamine* 3,5-*Dinitrobenzoate*.—To a solution of (±)-3-*p*-chlorophenyl-*NN*-dimethyl-3-2′-pyridylpropylamine (249 g.) in isopropyl acetate (1 l.) was added a solution of 3,5-dinitrobenzoic acid (192 g.) in acetone (375 ml.). The salt, which was filtered off, washed with isopropyl acetate, and dried, had m. p. 132° (Found: C, 57·05; H, 4·9; Cl, 7·6; N, 11·9. $C_{23}H_{23}ClN_4O_6$ requires C, 56·7; H, 4·8; Cl, 7·3; N, 11·5%).

(+)-3-p-*Chlorophenyl*-NN-*dimethyl*-3-2′-*pyridylpropylamine* 3,5-*Dinitrobenzoate*.—(a) *From* (+)-*base*. 3,5-Dinitrobenzoic acid (7·8 g.) and (+)-base (10 g.) were dissolved in boiling acetone (180 ml.). The crystals which separated on cooling were twice recrystallised from acetone, giving the *salt* [" the (+)-dinitrobenzoate "], m. p. 146°, $[\alpha]_D$ +54·6° (*c* 2·1 in $CHCl_3$) (Found: C, 57·0; H, 4·8; Cl, 6·9; N, 11·25%).

(b) *From the dinitrobenzoate of* (±)-*base, by seeding*. 3,5-Dinitrobenzoic acid (1·93 g.) and (±)-base (2·5 g.) were dissolved in warm acetone (50 ml.), and the solution was cooled to room temperature. The supersaturated solution was seeded with a few crystals (<0·5 mg.) of " (+)-dinitrobenzoate " and was set aside overnight. The salt which separated (0·35 g.) had m. p. 144—145°, and $[\alpha]_D$ +33° (*c* 1 in $CHCl_3$), corresponding to 60·4% of the (+)-isomer. Thus a 9·5% resolution of the racemic base had occurred.

[7] Houben-Weyl, " Methoden der Organischen Chemie," 4th edn., 1955, Vol. IV, 509; Anderson and Hill, *J.*, 1928, 993; Zaugg, *J. Amer. Chem. Soc.*, 1955, **77**, 2910; Potanov, *Uspekhi Khim.*, 1957, **26**, 1152; B.P. 709,595.

[8] Stoll and Hofmann, *Helv. Chim. Acta*, 1943, **26**, 922.

[9] Hunt, *J.*, 1957, 1925.

(−)-3-p-*Chlorophenyl*-NN-*dimethyl*-3-2′-*pyridylpropylamine* 3,5-*Dinitrobenzoate*.—Partially resolved (−)-base (50 g.; $[\alpha]_D$ −15°) obtained from the mother-liquors after collection of the (+)-di-*p*-toluoyltartrate of the (+)-base} and 3,5-dinitrobenzoic acid (39 g.) were dissolved in hot acetone (200 ml.) and the mixture evaporated to dryness *in vacuo*. The hard crystalline cake which remained was digested twice for 0·25 hr. with boiling isopropyl acetate (200 ml.). The remaining solid, after two recrystallisations from isopropyl acetate (1070 ml.), had $[\alpha]_D$ −49° (44 g.). Three recrystallisations from acetone gave the pure *salt* (30 g.), m. p. 145—146°, $[\alpha]_D$ −54·6° (*c* 2·1 in $CHCl_3$) (Found: C, 56·4; H, 4·55; Cl, 7·5; N, 11·75%).

Resolution of (±)-3-p-*Chlorophenyl*-NN-*dimethyl*-3-2′-*pyridylpropylamine* 3,5-*Dinitrobenzoate*. —(±)-Base (100 g.), 3,5-dinitrobenzoic acid (38·6 g., 0·5 equiv.), and " (+)-3,5-dinitrobenzoate " [26·6 g., providing a 30% excess of the (+)-base] were dissolved in warm ethyl methyl ketone (1300 ml.). The solution was allowed to cool to room temperature and was then seeded with " (+)-dinitrobenzoate " (0·1 g.). The salt which crystallised overnight (72·5 g.) had m. p. 143°, and $[\alpha]_D$ +38·9° corresponding to 72·2% of the (+)-isomer and a 29% resolution of the (±)-base. " (±)-Dinitrobenzoate " (71·5 g.) was then added to the mother-liquors which then contained (±)-base (100 g.) and (−)-base (14·5 g., 29% excess). Solvent was added to restore the original volume and, after being heated until all had dissolved, the solution was allowed to cool and was then seeded with " (−)-dinitrobenzoate " (0·1 g.). The second crop of salt (69 g.) had $[\alpha]_D$ −44·8° and thus contained 83% of (−)-isomer, representing a resolution of 35·6%. This procedure was repeated until a total of 672 g. of (±)-base had been added (as dinitrobenzoate) and 18 crops of salt [alternately (+) and (−)] of optical purity 72—94% had been obtained, corresponding to 277 g. of (+)-base and 273 g. of (−)-base. The (+)-dinitrobenzoate (248 g.), recrystallised from acetone (2500 ml.), gave (+)-chlorpheniramine 3,5-dinitrobenzoate (204 g.), m. p. 145—146°, $[\alpha]_D$ +53·35° (*c* 2 in $CHCl_3$). The purified salt was suspended in water (1 l.) and basified with N-sodium hydroxide solution (500 ml.), and the base extracted into benzene (1500 ml.). The benzene extract was washed with water, dried by azeotropic distillation (*ca.* 200 ml.), and treated with a solution of maleic acid (48 g.) in hot acetone (300 ml.). (+)-Chlorpheniramine hydrogen maleate (151 g., 92%) which separated was filtered off, washed with benzene, and dried *in vacuo* at 60°. It had m. p. 113—114°, $[\alpha]_D$ +23·1° (*c* 1·6 in H_2O) and was identical with that prepared from base resolved with di-*p*-toluoyltartaric acid. Similarly from recrystallised " (−)-dinitrobenzoate " {m. p. 145—146°, $[\alpha]_D$ −54·1 (*c* 2 in $CHCl_3$)} was obtained (−)-chlorpheniramine hydrogen maleate, m. p. 113°, $[\alpha]_D$ −23·7° (*c* 1·2 in H_2O).

Resolution of Pheniramine.—(±)-*NN*-Dimethyl-3-phenyl-3-2′-pyridylpropylamine (24 g.) and (−)-*OO*-di-*p*-toluoyltartaric acid (19·3 g.) were dissolved, by warming, in N-hydrochloric acid (50 ml.), ethanol (100 ml.), and water (50 ml.). The solution was cooled, crystallisation was induced by scratching, and the mixture was left overnight. The crystals which separated (31·5 g.; m. p. 144°) were thrice recrystallised from aqueous ethanol (50%), giving impure (− −)-*NN*-dimethyl-3-phenyl-3-2′-pyridylpropylamine *OO*-di-*p*-toluoyltartrate (19 g.), m. p. 147—148°, $[\alpha]_D^{21}$ −90° (*c* 2 in EtOH) (unchanged on further recrystallisation). The salt was suspended in water, and 5N-sodium hydroxide (25 ml.) was added. The base obtained by ether-extraction {6·5 g., $[\alpha]_D$ −8° (*c* 9 in EtOH)} was dissolved in isopropyl acetate (50 ml.) and treated with a solution of 3,5-dinitrobenzoic acid (5·3 g.) in acetone (15 ml.). The solid which separated was recrystallised five times from acetone, giving (−)-NN-*dimethyl*-3-*phenyl*-3-2′-*pyridylpropylamine* 3,5-*dinitrobenzoate*, m. p. 169—170°, $[\alpha]_D^{20}$ −54·0° (*c* 1·15 in $CHCl_3$) (Found: C, 61·1; H, 5·3; N, 12·6. $C_{23}H_{24}N_4O_6$ requires C, 61·05; H, 5·35; N, 12·4%).

The dinitrobenzoate (2·5 g.) was suspended in water, N-sodium hydroxide was added, the liberated base was extracted into ether, and the ethereal solution was dried (KOH) and evaporated. The residual oil was distilled, giving (−)-NN-*dimethyl*-3-*phenyl*-3-2′-*pyridylpropylamine*, b. p. 113°/0·2 mm., n_D^{21} 1·5542, $[\alpha]_D^{19}$ −36·3° (*c* 1·3 in EtOH) (Found: C, 79·7; H, 8·6; N, 11·4. $C_{16}H_{20}N_2$ requires C, 80·0; H, 8·4; N, 11·7%).

The *hydrogen maleate*, prepared in isopropyl acetate from the (−)-base and maleic acid, after two recrystallisations from isopropyl acetate had m. p. 97—98°, $[\alpha]_D^{22·5}$ −30·4° (*c* 1 in H_2O) (Found: C, 67·5; H, 6·6; N, 8·1. $C_{20}H_{24}N_2O_4$ requires C, 67·4; H, 6·8; N, 7·9%). The base (13 g.) obtained from the original (− −)-di-*p*-toluoyltartrate mother-liquors by basification with 5N-sodium hydroxide was similarly treated with 3,5-dinitrobenzoic acid. The salt obtained was recrystallised seven times from acetone, giving (+)-NN-*dimethyl*-3-*phenyl*-3-2′-*pyridylpropylamine* 3,5-*dinitrobenzoate*, m. p. 169°, $[\alpha]_D^{19}$ +55·1° (*c* 1·2 in $CHCl_3$) (Found: C, 60·8; H, 5·4; N, 12·2%).

XUM

This was converted as for the (−)-isomer into (+)-NN-*dimethyl*-3-*phenyl*-3-2′-*pyridylpropylamine*, b. p. 116°/0·2 mm., $n_D^{17\cdot5}$ 1·5550, $[\alpha]_D^{19}$ +37·5° (*c* 2 in EtOH) (Found: C, 80·35; H, 8·6; N, 11·25. $C_{16}H_{20}N_2$ requires C, 80·0; H, 8·4; N, 11·7%). The *hydrogen maleate*, prepared as above, after recrystallisation from isopropyl acetate had m. p. 95—96°, $[\alpha]_D^{22}$ +30·9° (*c* 2 in H_2O) (Found: C, 67·2; H, 6·85; N, 7·9%).

(±)-NN-*Dimethyl*-3-*phenyl*-3-2′-*pyridylpropylamine* 3,5-*Dinitrobenzoate*.—(±)-*NN*-Dimethyl-3-phenyl-3-2′-pyridylpropylamine (37 g.) in acetone (350 ml.) was treated with a solution of 3,5-dinitrobenzoic acid (33 g.) in acetone (150 ml.). The solid which separated on cooling was recrystallised from acetone, giving the *salt* (54 g.), m. p. 157° (Found: C, 61·55; H, 5·4; N, 12·3%).

Resolution of Pheniramine 3,5-*Dinitrobenzoate*.—(±)-*NN*-Dimethyl-3-phenyl-3-2′-pyridylpropylamine (5 g.) and 3,5-dinitrobenzoic acid (2·2 g.) were dissolved in warm ethyl methyl ketone (150 ml.), and the solution was cooled to room temperature and seeded by adding crystals of the dinitrobenzoate of the (−)-base (0·06 g.). The salt which separated overnight (3·6 g.) had m. p. 154° and $[\alpha]_D$ −4·6° and thus contained 8·4% of the (−)-isomer. This represents a resolution of 5·1%. Racemic dinitrobenzoate (3·8 g.) was added to the mother-liquors, and the solvent was made up to the original volume. The salt was dissolved by heating and the solution was again cooled and seeded with a trace of the dinitrobenzoate of the (+)-base. The second crop of salt (2·25 g.) had m. p. 160°, and $[\alpha]_D$ +39·6° corresponding to 72% of the (+)-isomer and a resolution of 29%. This procedure was repeated until 9 crops had been collected during which 16 g. of (±)-base had been added. Several recrystallisations of the optically impure salts [7·75 g. of (+)-salt, 69% pure; 11·8 g. of (−)-salt, 49% pure] gave the pure dinitrobenzoate of (+)-pheniramine, with m. p. 168° and $[\alpha]_D$ +55·7°, and of (−)-pheniramine with m. p. 168°, $[\alpha]_D$ −55·3° (*c* 2 in $CHCl_3$).

The author thanks Miss P. R. Schaay and Mr. R. Hornby for technical assistance.

RESEARCH DIVISION, ALLEN & HANBURYS LTD.,
WARE, HERTS.

[*Received, November 25th*, 1960.]

---

423. *The Reaction of α-Pinene with Lead Tetra-acetate.*

By G. H. WHITHAM.

The primary product from the reaction of α-pinene with lead tetra-acetate in benzene has been shown to be *cis*-2-acetoxypin-3-ene (III; R = Ac). This unsaturated acetate undergoes rapid allylic rearrangement to *trans*-verbenyl acetate (II) in acetic acid.

IN an investigation of the reaction of α-pinene (I) * with lead tetra-acetate in acetic acid Matsubaara [1] obtained a complex mixture containing alcohol monoacetates, glycol diacetates, and hydrocarbons. However, under the conditions used, allylic acetates might be expected to undergo further reactions so that information as to the primary product of the reaction is lost. Criegee,[3] on the other hand, has reported that when benzene is used as solvent *trans*-verbenyl acetate (II) is formed. In his hands the use of acetic acid as solvent led to two additional products, sobrerol diacetate and verbenene, along with *trans*-verbenyl acetate.

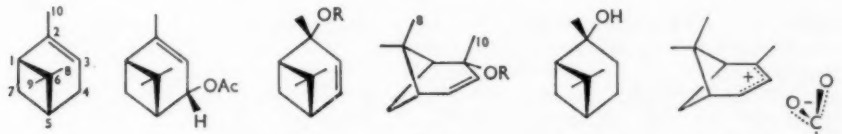
Since verbenol was required in connection with other studies [4] we re-investigated the reaction of α-pinene with lead tetra-acetate in benzene and find that it follows a hitherto unsuspected course.

* The formulæ used in this paper correspond to the absolute configuration of (+)-α-pinene.[2] α-Pinene used in the experiments to be described was optically impure but contained a preponderance of the (+)-isomer.

[1] Matsubaara, *J. Chem. Soc. Japan*, 1957, **78**, 907, 909; cf. *Chem. Abs.*, 1959, 22056.
[2] Birch, *Ann. Reports*, 1950, **47**, 191.
[3] Criegee, *Angew. Chem.*, 1958, **70**, 173.
[4] Hurst and Whitham, *J.*, 1960, 2864.

On addition of dry lead tetra-acetate to α-pinene in benzene at 65° a smooth reaction occurred and lead diacetate was precipitated. Criegee [3] describes a working-up procedure which involves filtration of the precipitate and subsequent evaporation and distillation. However, this is complicated by the further precipitation of lead salts during the evaporation so that we employed an alternative method, *viz.*, addition of water to the filtrate followed by removal of precipitated lead dioxide by a second filtration. In this way an unsaturated acetate, $C_{12}H_{18}O_2$, was isolated which was not *trans*-verbenyl acetate since it did not give *trans*-verbenol on alkaline hydrolysis. That the unsaturated alcohol thus obtained was *cis*-pin-3-en-2-ol (III; R = H) (*i.e.* a derivative of *cis*-pinane) was shown in the following way. It exhibited a strong infrared band at 733 cm.$^{-1}$, attributable to a *cis*-disubstituted double bond, and on hydrogenation in ethanol over palladium–carbon one mol. of hydrogen was absorbed, giving a saturated alcohol which had no infrared band at 733 cm.$^{-1}$. Identity of the latter alcohol with *cis*-pinan-2-ol [5] (IV) was shown by comparison with an authentic sample obtained by reduction of β-pinene epoxide with lithium aluminium hydride; it was characteristically different from *trans*-pinan-2-ol.

The primary product from the reaction of lead tetra-acetate with α-pinene in benzene is thus *cis*-2-acetoxypin-3-ene (III; R = Ac). In agreement, the infrared spectrum showed a strong band at 745 cm.$^{-1}$ (*cis*-disubstituted double bond).



(I) (II) (IIIa) (IIIb) (IV) (V)

It was found that the unsaturated acetate (III; R = Ac) undergoes very ready allylic rearrangement in acetic acid at 20° with the formation, in high yield, of *trans*-verbenyl acetate (II). The latter was identified by alkaline hydrolysis to the known *trans*-verbenol. The rearrangement could be followed by the large change in rotation. In glacial acetic acid the reaction was complete after 5 min. at 20°. It was rather slower in 80% acetic acid in dioxan and a rough kinetic run showed first-order behaviour with a rate constant of *ca.* $2{\cdot}5 \times 10^{-3}$ sec.$^{-1}$ at 20°. Since this very ready rearrangement requires a good ionising solvent and does not occur, for example, on distillation, it is considered to proceed *via* the ion-pair (V) in accordance with the observed stereochemistry of the reaction. The rate-determining ionisation would be facilitated by the release of strain associated with the non-bonded 1,3-diaxial interaction between the 8- and the 10-methyl group (cf. IIIb). Quantitative conversion into *trans*-verbenyl acetate reflects the superior thermodynamic stability of the latter relative to the acetate (III; R = Ac).

It is of interest that although the ion (V) bears a partial positive charge at $C_{(2)}$, skeletal rearrangement to the bornylene system does not occur under these conditions. This contrasts with the rearrangement accompanying solvolysis of the 3,5-dinitrobenzoate of *cis*-pinan-2-ol (IV) which furnishes the 3,5-dinitrobenzoate of borneol.[6] In the present instance the fact that skeletal rearrangement does not intrude is probably due to the high energy content of the bicyclo[2,2,1]hept-2-ene system.[7]

Criegee's observations on the α-pinene–lead tetra-acetate reaction in benzene are readily accommodated by the present results since working up of the reaction mixture under his conditions involves distillation in the presence of the acetic acid produced in the reaction.

[5] Vilkas, Dupont, and Dulou, *Compt. rend.*, 1956, **242**, 1329; Vilkas, *Bull. Soc. chim. France*, 1959, 1401; Burrows and Eastman, *J. Amer. Chem. Soc.*, 1959, **81**, 245.

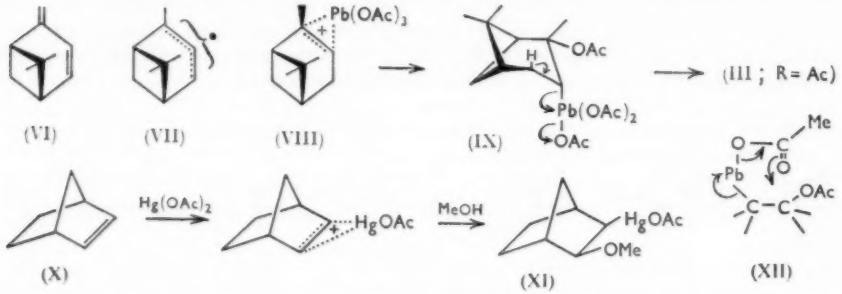
[6] Abraham and Vilkas, *Bull. Soc. chim. France*, 1960, 1450; Abraham, *Ann. Chim.* (*France*), 1960, 961.

[7] Wheeler, Cetina, and Zabicky, *J. Org. Chem.*, 1957, **22**, 1153; Schleyer, *J. Amer. Chem. Soc.*, 1958, **80**, 1700.

XUM

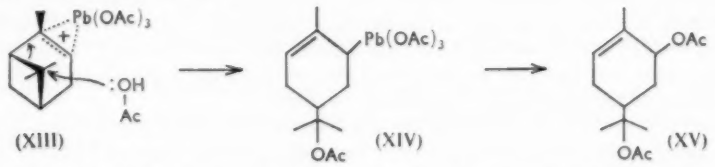
Allylic rearrangement apparently occurred at this stage. In confirmation, a repetition of the reaction with strict adherance to the Criegee procedure gave *trans*-verbenyl acetate identical with that obtained above. From the preparative point of view it is preferable to isolate the intermediate acetate (III; R = Ac) and carry out the rearrangement under controlled conditions. On one occasion use of Criegee's method on a larger scale led to a substantial quantity of verbenene (VI), derived by elimination of acetic acid, along with a reduced yield of *trans*-verbenyl acetate.

The exclusive formation of *cis*-2-acetoxypin-3-ene (III; R = Ac) in the lead tetra-acetate reaction is of interest in connection with the mechanism of lead tetra-acetate–olefin reactions in general. A free-radical route involving the intermediate radical (VII) seems unlikely since, on this basis, the formation of at least a significant proportion of verbenyl acetate, resulting from attack at $C_{(4)}$, would be expected. On the other hand, electrophilic attack of lead tetra-acetate on α-pinene, from the side remote from the gem-dimethyl bridge, to give the bridged intermediate (VIII) * could be followed by *cis*-Markownikow



opening to form the intermediate addition product (IX). Oxidative decomposition of the latter by elimination as shown would give the observed product, acetic acid and lead diacetate. Precedence for the *cis*-opening of a bridged ion of type (VIII) may be claimed in the reaction of norbornene with mercuric acetate, which proceeds as shown (X ⟶ XI).[8] In the case of the ion (VIII) the stereoelectronically more probable process of *trans*-diaxial opening would involve severe steric interaction between the incoming acetate moiety and the 8-methyl group.

Criegee [3] has postulated intermediates of type (IX) to rationalise the addition of two acetate residues across the double bond in the reaction of lead tetra-acetate with certain olefins. In such cases the intermediate is considered to decompose as in (XII). The decomposition route proposed for intermediate (IX) is a *trans*-diaxial elimination and represents an alternative mode of breakdown of a Criegee intermediate. In the present case it may be preferred because it releases strain associated with the boat "flagpole" substituents at positions 3 and 7.



It seems likely that decomposition of a Criegee intermediate by elimination may be significant in other cases where the reaction of lead tetra-acetate with an olefin leads to

* This intermediate ion is the analogue of a bromonium ion, *viz.*:

[8] Traylor and Baker, *Tetrahedron Letters*, 1959, No. 19, 14.

apparent allylic substitution by an acetoxyl group, *e.g.*, the formation of cyclohex-2-enyl acetate from cyclohexene.[3]

Our scheme also explains Criegee's isolation of sobrerol diacetate (XV): this may be derived from the intermediate ion (VIII) by the route (XIII ⟶ XIV ⟶ XV).

Experimental

Infrared spectra and rotations were taken for carbon disulphide and chloroform solutions respectively. Light petroleum refers to the fraction of b. p. 40—60°.

cis-2-*Acetoxypin*-3-*ene*.—α-Pinene [27 g., freshly redistilled, $[\alpha]_D$ +28° (*c* 2·0)] in dry benzene (500 c.c.) was warmed to 65° and lead tetra-acetate (84 g., dried over phosphorus pentoxide) was added during 20 min. to the stirred solution, the temperature being maintained at 60—65°. After an initial bright yellow coloration, gradual precipitation of lead diacetate occurred. On completion of the addition the suspension was stirred at 60—65° for a further 30 min. After cooling and filtration the filtrate was added to water, and precipitated lead dioxide was removed. Evaporation of the dried benzene layer followed by distillation gave cis-2-*acetoxypin*-3-*ene* (21·2 g., 55%), b. p. 96—97°/9 mm., n_D^{21} 1·4735, $[\alpha]_D$ −78° (*c* 1·9) (Found: C, 74·5; H, 9·5. $C_{12}H_{18}O_2$ requires C, 74·2; H, 9·35%). Strong bands in the infrared spectrum at 1109, 920, 840, and 748 cm.$^{-1}$ served to distinguish it from *trans*-verbenyl acetate which is transparent in these regions. The absence of bands at 970 and 773 cm.$^{-1}$ indicated that verbenyl acetate was not present.

cis-*Pin*-3-*en*-2-*ol*.—*cis*-2-Acetoxypin-3-ene (18·7 g.) in aqueous-methanolic 10% potassium hydroxide (100 c.c.) was set aside at 20° for 16 hr. After removal of most of the methanol by distillation, water was added and the product was isolated with ether. Distillation gave cis-*pin*-3-*en*-2-*ol* (11·2 g., 76%), b. p. 84—88°/10 mm., n_D^{23} 1·4852 (Found: C, 78·95; H, 11·0. $C_{10}H_{16}O$ requires C, 78·9; H, 10·6%). The highly characteristic infrared spectrum was quite different from that of *trans*-verbenol and had strong bands at, *inter alia*, 900 and 733 cm.$^{-1}$.

cis-*Pinan*-2-*ol*.—*cis*-Pin-3-en-2-ol (2 g.) was stirred with pre-reduced Adams platinum catalyst (50 mg.) in ethanol (50 c.c.) under hydrogen (absorption 300 c.c., 0·94 mol.). After filtration the solution was evaporated and the residue was filtered in light petroleum through a short column of alumina. Evaporation of the eluate gave *cis*-pinan-2-ol (1·98 g.), m. p. (after sublimation) 74—77° undepressed on admixture with a sample (m. p. 76—77°) prepared by reduction of β-pinene epoxide with lithium aluminium hydride.[5] The infrared spectra of the two samples were rich in detail and virtually identical. *trans*-Pinan-2-ol prepared from methylmagnesium iodide and nopinone had a very different infrared spectrum.

Rearrangement of cis-2-*Acetoxypin*-3-*ene*.—(i) *cis*-2-Acetoxypin-3-ene (5 g.) in glacial acetic acid (25 c.c.) was set aside at 20° for 30 min. After addition of water and ether-extraction the extract was washed with aqueous sodium carbonate. Evaporation of the dried solution followed by distillation gave *trans*-verbenyl acetate (4·25 g.), b. p. 97—98°/9 mm., n_D^{20} 1·4731, $[\alpha]_D$ +77° (*c* 2·1). The infrared spectrum was characteristically different from that of starting material: two diagnostic bands occur at 970 and 773 cm.$^{-1}$ in regions of only low absorption for *cis*-2-acetoxypin-3-ene.

The *trans*-verbenyl acetate was identified by alkaline hydrolysis to trans-verbenol, b. p. 91—92°/6 mm., $[\alpha]_D$ +66° (*c* 2·0); the highly characteristic infrared spectrum of the latter was identical with that of an authentic sample. This value for the specific rotation of the *trans*-verbenol corresponds to 40% optical purity on the basis of +168° for (+)-*trans*-verbenol.[9] The α-pinene used in the lead tetra-acetate reaction had an optical purity of 55% based on the value +51° for (+)-α-pinene.[10] Since optical fractionation should not have occurred during the isolation procedure the reason for this discrepancy is not clear, however, in view of the various errors involved it is not considered to be serious.

(ii) A solution of *cis*-2-acetoxypin-3-ene (2·08 g./100 c.c.) in 80% acetic acid–dioxan (8 vol. of glacial acetic acid made up to 10 vol. with dioxan) was made and rapidly transferred to a polarimeter tube; readings were taken at intervals during 15 min. and are tabulated. The zero reading was calculated from the known specific rotation of *cis*-2-acetoxypin-3-ene in chloroform. The infinity reading +0·76° was in good agreement with the specific rotation of *trans*-verbenyl

[9] Elsevier's "Encyclopedia of Organic Chemistry," Vol. 12A, Elsevier, Amsterdam 1948, p. 505.
[10] Ref. 9, p. 456.

XUM

acetate. First-order rate constants were calculated in the usual way and are tabulated. The average value for the rate constant for the reaction, obtained graphically, is $2{\cdot}48 \times 10^{-3}$ sec.$^{-1}$ at 20°.

t (sec.)	0	180	270	330	390	450	510
[α]	−0·76°	−0·16°	−0·02°	+0·11°	+0·18°	+0·27°	+0·35°
10^3k (sec.$^{-1}$)	—	2·77	2·48	2·57	2·46	2·51	2·57
t (sec.)	570	630	690	750	810	870	∞
[α]	+0·38°	+0·42°	+0·48°	+0·52°	+0·57°	+0·59°	+0·76°
10^3k (sec.$^{-1}$)	2·43	2·38	2·45	2·45	2·57	2·52	—

The author thanks Drs. G. Buchanan (Glasgow) and H. Schmidt (Leipzig) for authentic samples of *trans*-verbenol.

CHEMISTRY DEPARTMENT, THE UNIVERSITY,
BIRMINGHAM, 15.

[*Received, December 16th*, 1960.]

---

424. *The Thermodynamic Properties of Organic Oxygen Compounds. Part II.*[1] *Vibrational Assignment and Calculated Thermodynamic Properties of Phenol.*

By J. H. S. GREEN.

A complete vibrational assignment of phenol is correlated with those of *o*-phen[^{2}H]ol, toluene, fluorobenzene, and aniline. The thermodynamic functions are tabulated for phenol in the ideal-gas state from 0° to 1000° K.

THE vibrational spectra of phenol have been measured several times and partial assignments of the fundamentals have been made by Kohlrausch and Wittek [2] from the Raman spectrum and by Mecke and his co-workers [3] from the infrared spectrum. Davies and Jones [4] discussed the infrared spectrum of *o*-phen[^{2}H]ol in relation to that of phenol and considered the modes associated with the hydroxyl group. In the present work a complete vibrational assignment is made from which, in conjunction with molecular structure data, including the barrier height to free rotation of the hydroxyl group,[5] the thermodynamic functions are calculated.

ASSIGNMENT

The spectra are collected in Table 1, where the depolarisation ratios of the Raman lines are those of Kohlrausch and Wittek.[2] As they provide important additional information, the infrared spectra of phenol vapour and of *o*-phen[^{2}H]ol, in carbon disulphide solution and in the solid, are also tabulated. The phenol molecule has approximately C_{2v} symmetry and the fundamental vibrations, exclusive of those associated with the hydroxyl group, divide into $11a_1 + 10b_1 + 3a_2 + 6b_2$. All the species are Raman active, but only those of the a_1 class are polarised, the rest being depolarised, whilst in the infrared the a_1, b_1, and b_2 vibrations can yield approximately type *A*, *B*, and *C* contours, respectively, the a_2 species being inactive. The complete assignment for phenol is given in Table 2, where the approximate description of the modes is that of Whiffen [6] and the numbering is that of Wilson.[7]

The majority of these assignments follow in a straightforward way from those of other

[1] The paper, Andon, Biddiscombe, Cox, Handley, Harrop, Herington, and Martin, *J.*, 1960, 5246, is to be regarded as Part I.
[2] Kohlrausch and Wittek, *Monatsh.*, 1943, **74**, 1.
[3] (*a*) Mecke and Rossmy, *Z. Elektrochem.*, 1955, **59**, 86; (*b*) Mecke and Greinacher, *ibid.*, 1957, **61**, 530.
[4] Davies and Jones, *J.*, 1954, 120.
[5] Kojima, *J. Phys. Soc. Japan*, 1960, **15**, 284.
[6] Whiffen, *J.*, 1956, 1350; Randle and Whiffen, "Molecular Spectroscopy," Conference held by the Institute of Petroleum, London, 1954.
[7] Wilson, *Phys. Rev.*, 1934, **45**, 706.

TABLE 1. *Vibrational spectra of phenol and* o-*phen*[^{2}H]*ol.*

C_6H_5·OH				C_6H_5·O^{2}H			
Raman (melt)		Infrared		Infrared			
$\Delta\nu$ (cm.$^{-1}$)	ρ [a]	Vapour [b]	CCl_4 soln.	CS_2 soln. [c]	Crystal [d]	Assignment
241(s)	0·79					b_2 fundamental
415(vw)		408(4)				b_1 and a_2 fundamentals
507(w)		496(5) 502(6)	502(w)			b_2 fundamental
532(s)	0·72	514(sh) 526(3) 533(sh)	526(w)			a_1 fundamental
617(s)	0·84	591(1)	617(w)			b_1 fundamental
		681(4) 686(8) *C* 691(4)	688(s)	690(s)	689(9)	b_2 fundamental
756(s)	[0·60]	742(7) 747(9) *C* 751(7)	752(s)	750(s)	754(10)	b_2 fundamental
812(s)	0·13	806(sh) 810(5) *A* 814(5)	810(s)	805(m)	805(9)	a_1 fundamental
828(m)		823(5) 828(sh)	825(m)	—	821(sh)	a_2 fundamental
		875(sh) 881(4) *C* 888(sh)	884(m)	885(m)	879(sh) 887(7)	b_2 fundamental
				910(s)	932(sh)	C–O–D bending fundamental
			958(vw)		961(7)	a_2 fundamental
			978(vw)		976(8)	b_2 fundamental
995(vw)						756 + 240 = 996 (A_1)
1002(s)	0·07	999(1)	1000(m)	1000(m)	995(8)	a_1 fundamental
1014(vw)						507 + 507 = 1014 (A_1)
		1015(1) 1026(1) *A* 1033(1)	1024(m)	1024(w)	1020(sh)	a_1 fundamental
1072(m)		1057(3) *B* 1069(sh)	1071(m)	1070(m)	1074(9)	b_1 fundamental
			1106(w)		1104(4)	688 + 415 = 1103 (A_2 or B_1)
1152(m)	0·64	1142(sh) 1148(6)	1153(m)	1148(m)	1152(8)	b_1 fundamental
1167(5)	0·64	1167(9) 1175(10) 1182(10) 1196(sh)	1167(s) 1182(s)	1170(vw)	1166(7)	a_1 fundamental C–O–H bending fundamental
			1220(s)	1220(sh)	1223(sh)	688 + 500 = 1188 (A_1) 408 + 810 = 1218 (A_2 or B_1)
1250(m)		1253(sh) *A* 1259(9)	1255(s)	1242(s)	1242(9)	a_1 fundamental
					1284(s)	[*530*] + *754* = *1284* (B_2)
				1300(vw)	1300(s)	[*500*] + *805* = *1305* (B_2)
		1310(sh)	1313(w)		1316(3)	b_1 fundamental
		1333(5)	1322(sh)			
		1344(5)	1344(m)	1330(vw)	1332(4)	b_1 fundamental; 502 + 825 = 1327 (B_1)
		1349(5)				823 + 526 = 1349 (A_2) 810 + 526 = 1336 (A_1)
					1362(5)	[*400*] + *961* = *1361* (A_1 or B_2)
1381(vw)			1384(m)		1383(4)	500 or [500] + 887 = 1387 (A_1)
1466(w)		1460(sh) 1471(sh)	1472(s)	1456(s)	1456(8) 1471(sh)	b_1 fundamental
1498(w)		1492(8) 1497(8) *A* 1506(sh)	1498(s)		1493(9)	a_1 fundamental
			1527(w)		1520(sh) 1543(2)	526 or [*530*] + 1000 = 1526, [1530] (A_1)
1595(vs)	0·74	1600(9)	1596(s)	1600(s)	1585(9)	a_1 fundamental
1604(vs)	0·74		1604(sh)		1592(sh)	b_1 fundamental
					1634(sh)	*821* + *821* = *1642* (A_1)
			1707(w)	1690(vw)	1698	825 + 884 = 1709 (B_1); *821* + *887* = *1708* (B_1)
			1777	1760(vw)	1761	884 + 884 = 1768 (A_1); 887 + 887 = 1774 (A_1)

TABLE 1. (*Continued.*)

$C_6H_5{\cdot}OH$				$C_6H_5{\cdot}O^2H$		
Raman (melt)		Infrared		Infrared		
$\Delta\nu$ (cm.$^{-1}$)	ρ [a]	Vapour [b]	CCl_4 soln.	CS_2 soln.[c]	Crystal [d]	Assignment
			1810			$825 + 978 = 1803$ (B_1)
			1842	1840(vw)	1835	$884 + 958 = 1842$ (B_1); *887 + 961 = 1848* (B_1)
				1920(vw)	1916(4)	*961 + 961 = 1922* (A_1)
			1932(w)		1934(sh)	$958 + 978 = 1936$ (B_1); *961 + 973 = 1934* (B_1)
			1950(w)			$978 + 978 = 1956$ (A_1)
				2650(m)	2370	O–D stretching fundamental
3027(0) [a]		3030(5)	3023(sh)			b_1 fundamental
3047(5*b*) [a]			3046(m)			a_1 fundamental
3063(8*b*) [a]						a_1 fundamental
			3076(m)			a_1 fundamental
3085($\frac{1}{2}$) [a]			3091			b_1 fundamental
		3623(6)	3612(m)			O–H stretching fundamental

[a] Depolarisation ratios as given by Kohlrausch and Wittek.[2] [b] Mecke, D.M.S. Catalogue of Infrared Spectra, Butterworths, London, No. 3344. [c] Mecke, D.M.S. Catalogue of Infrared Spectra, Butterworths, London, No. 3690. [d] Mecke and Greinacher, *Z. Elektrochem.*, 1957, **61**, 530. Italicised summations relate to $C_6H_5{\cdot}OD$. [ ] inferred from combination bands.

TABLE 2. *Correlation of the fundamental frequencies* (cm.$^{-1}$) *of phenol,* o-*phen*[^{2}H]*ol, toluene, fluorobenzene, and aniline.*

	Mode [a]	No.[7]	Phenol	*o*-Phen[^{2}H]ol	Toluene	Fluorobenzene	Aniline
a_1	ν(CH)	20*a*	3085	—	3067	3084	3073
	ν(CH)	2	3076	—	3056	3053	3050
	ν(CH)	13	3044	—	3003	3040	3058
	ν(CC)	8*a*	1596	1600	1585	1603	1600
	ν(CC)	19*a*	1497	1493	1492	1496	1498
	β(CH)	9*a*	1167	1170	1178	1156	1171
	β(CH)	18*a*	1026	1024	1030	1021	1027
	Ring	1	999	1000	1004	1010	994
	X-sens.	7*a*	1259	1242	1208	1218	1277
	X-sens.	12	810	805	786	807	818
	X-sens.	6*a*	526	[530]	521	519	531
b_1	ν(CH)	20*b*	3091	—	3090	3098	3073 *
	ν(CH)	7*b*	3030	—	3039	3072	3050 *
	ν(CC)	8*b*	1604	1600 *	1604	1596	1600 *
	ν(CC)	19*b*	1465	1456	1455	1459	1464
	ν(CC)	14	1333	1330	1330	1325	1340
	β(CH)	3	1313	1316	1313	1295	1311
	β(CH)	9*a*	1145	1148	1155	1156 *	1154
	β(CH)	15	1071	1070	1081	1066	1054
	α(CCC)	6*b*	617	—	623	615	619
	X-sens.	18*b*	408	~[400]	344	406	388
a_2	γ(CH)	17*a*	958	961	966	955	964
	γ(CH)	10*a*	825	821	843	830	833
	ϕ(CC)	16*a*	408 *	~[400]	407	406 *	415
b_2	γ(CH)	5	978	973	981	980	988
	γ(CH)	17*b*	881	885	895	896	886
	γ(CH)	10*b*	749	750	729	754	758
	ϕ(CC)	4	688	690	695	685	690
	X-sens.	16*b*	500	[500]	464	500	504
	X-sens.	11	241	—	216	242	233
	OH(OD) bending		1180	910			
	OH(OD) stretching		3623	~2650			

* Frequency used twice. (—) Frequency obscured, or not measured. [ ] Inferred from combination bands.

monosubstituted benzenes;[6] as is usual, the essentially CH stretching frequencies ν(CH) are not adequately resolved and the assignments given are rather arbitrary. Above 2000 cm.$^{-1}$ only frequencies assigned as fundamentals are given in Table 1, as several possibilities exist to account for the weak combination bands found in this region. The frequencies in the range 1630—1950 cm.$^{-1}$ are tabulated since their interpretation[8] in terms of the out-of-plane C–H deformation γ(CH) provides support for the assignments made for these modes.

Of the three frequencies arising from the hydroxyl group, one is the O–H stretching frequency, another is essentially the torsion of the group about the C–O bond, and the third is the C–O–H angular deformation, the assignment of which has caused some difficulty in the past. From the work of Davies[4] and of Mecke[3] it follows that the last value can be taken as 1180 cm.$^{-1}$; this absorption disappears on deuteration, and a new band appears at 910 cm.$^{-1}$ in dilute solution. This C–O–D bending fundamental give rise to a broad absorption from 930 to 980 cm.$^{-1}$ in the spectrum of the crystal, in which however the two γ(CH) frequencies at 961 and 973 cm.$^{-1}$ may be distinguished. The other assignments for the deuterated substance follow from those for phenol, and are listed in Table 2 with those for toluene, fluorobenzene, and aniline. In all these compounds the masses of the substituents are almost the same, and the changes in even the *X*-sensitive mode[6] are fairly small; again the assignments of the ν(CH) frequencies are rather arbitrary.

Of the C–C stretching frequencies ν(CC) only number 14, the lowest in the b_1 class, requires comment. From Mair and Hornig's assignment for benzene, a value near 1310 cm.$^{-1}$ is expected,[6] and in fluorobenzene the assignment at 1320 cm.$^{-1}$ is satisfactory. In phenol, however, there is found a doublet at 1332—1344 cm.$^{-1}$ which is virtually unchanged on deuteration.[4] This doublet may be due to Fermi resonance with the combination 502 + 825 = 1327 (B_1), and the fundamental is here assigned as 1333 cm.$^{-1}$. In toluene Wilmshurst and Bernstein[9] assigned it as 1155 cm.$^{-1}$; however, they recorded a depolarised Raman line at 1329 cm.$^{-1}$ and in several of the recorded infrared spectra of toluene[10] weak absorption is found at *ca.* 1333 cm.$^{-1}$. In Table 2, therefore, the fundamental has been assigned as 1330 cm.$^{-1}$ in toluene; the same value is given by Kovner and Peregudov.[11] Recently, Fuson, Garrigou-Lagrange, and Josien[12] have assigned this fundamental as 1494 cm.$^{-1}$, *i.e.*, degenerate with number 19*a*, but the present choice is better established.[6]

Also in the b_1 class is the in-plane C–H deformation β(CH), number 3, with a calculated value of 1295 cm.$^{-1}$ in deuterobenzene.[13] Again, in fluorobenzene the assignment is satisfactory, but in phenol the value seems to be somewhat higher and the weak absorption in solution at 1313 cm.$^{-1}$ is assigned to the fundamental. This band is just detectable as a shoulder at about 1310 cm.$^{-1}$ in the spectrum of the vapour. In toluene, Kovner and Peregudov gave 1278 cm.$^{-1}$ for this fundamental, but Wilmshurst and Bernstein[9] took the value 1105 cm.$^{-1}$ which seems much too low. Possible values available from the spectrum obtained by the latter workers are 1260 or 1311 cm.$^{-1}$ the latter of which is chosen here, and the weak absorption at 1105 cm.$^{-1}$ is taken as 695 + 407 = 1102 (B_1), in agreement with the observed type *B* contour. (Mecke and Greinacher[3b] similarly assigned the weak band in phenol at 1106 cm.$^{-1}$ as a b_1 fundamental but this is interpreted here as the same combination as in toluene.) Changes have also been made in two of the γ(CH) frequencies as given by Wilmshurst and Bernstein, their values 984 and 966 cm.$^{-1}$ in the a_2 and b_2 classes respectively being reassigned as 966 and 981 cm.$^{-1}$. These are in agreement with the more recent studies.[11,12]

[8] Whiffen, *Spectrochim. Acta*, 1955, **7**, 253.
[9] Wilmshurst and Bernstein, *Canad. J. Chem.*, 1957, **35**, 911.
[10] American Petroleum Institute, Research Project 44, Catalogue of Infrared Spectra, nos. 308, 1685, 1704, 1714, 1716, 1783.
[11] Kovner and Peregudov, *Optika i Spectroskopiya*, 1958, **5**, 134.
[12] Fuson, Garrigou-Lagrange, and Josien, *Spectrochim. Acta*, 1960, **16**, 106.
[13] Brodersen and Langseth, *Kgl. danske Videnskab. Selskab, Mat.-fys. Skrifter*, 1959, **1**, 3.

XUM

The assignments for aniline have been made on the basis of C_{2v} symmetry to facilitate the comparison and use has been made of the Raman shifts [1] apart from four frequencies (3058, 1311, 1054, 964 cm.$^{-1}$) taken from the infrared spectrum.[14] Essentially the same assignment has been recently made by Evans,[15] who attributes the Raman line at 1340 to a combination, assigning number 14 as an infrared band at 1330 cm.$^{-1}$ in the liquid. Again, therefore, the correlation with the other assignments in Table 2 is quite satisfactory.

Thermodynamic Functions

The values of the fundamental frequencies for phenol listed in Table 2 were used to calculate the vibrational contributions to the thermodynamic functions by using the tables of Johnston, Savedoff, and Belzer.[16] To compute the rotational contributions the following dimensions were used: C–C, 1·397 Å; C–H, 1·084 Å; C–O, 1·428 Å; C–O–H angle 107°; all other angles 120°. For this model the product of the three principal moments of inertia was found to be $2{\cdot}34 \times 10^{-113}$ g.^{3} cm.^{6}, and the reduced moment of inertia for internal rotation was found to be $1{\cdot}46 \times 10^{-40}$ g. cm.^{2}. The symmetry numbers are 1 for overall rotation and 2 for internal rotation. The barrier height to free rotation of the OH group was taken as 3140 ± 285 cal. as determined by Kojima,[5] and the contributions of restricted rotation to the thermodynamic functions were obtained from the tables of Pitzer and Gwinn.[17] Units, values of the fundamental constants, and atomic weights were those of the American Petroleum Institute Research Project 44.[18]

From the calculated values of the thermodynamic functions for phenol as listed in Table 3, together with those [16] for C (graphite), H_2 (g), and O_2 (g), and the experimental heat of formation of gaseous phenol,[1] the values of ΔH_f°, ΔG_f°, and $\log_{10} K_f$ were calculated for the reaction:

$$6C \text{ (graphite)} + 3H_2 \text{ (g)} + \tfrac{1}{2}O_2 \text{ (g)} = C_6H_5{\cdot}OH \text{ (g)}$$

The entropy of phenol was measured by Parks, Huffman, and Barmore [19] and, in

Table 3. *The molal thermodynamic properties of phenol in the ideal-gas state.*

T (°K)	$-(G^\circ - H_0^\circ)/T$ (cal./deg.)	$(H^\circ - H_0^\circ)/T$ (cal./deg.)	$(H^\circ - H_0^\circ)$ (kcal.)	S° (cal./deg.)	C_p° (cal./deg.)	$-\Delta H_f^\circ$ (kcal.) [a]	ΔG_f° [a] (kcal.)	$\log_{10} K_f$ [a]
0	0	0	0	0	0	18·63	−18·63	∞
273·16	60·17	13·18	3·60	73·35	22·70	22·72	−9·12	+7·30
298·16	61·36	14·07	4·19	75·43	24·75	23·05	−7·88	+5·78
300	61·45	14·13	4·24	75·58	24·90	23·07	−7·79	+5·68
400	66·01	17·79	7·12	83·80	32·45	24·12	−2·51	+1·37
500	70·37	21·37	10·68	91·74	38·64	24·92	+2·97	−1·30
600	74·56	24·67	14·80	99·23	43·54	25·55	+8·61	−3·14
700	78·59	27·65	19·36	106·24	47·44	26·06	+14·34	−4·48
800	82·46	30·33	24·26	112·79	50·62	26·40	+20·13	−5·50
900	86·18	32·73	29·46	118·91	53·26	26·65	+25·96	−6·30
1000	89·74	34·90	34·90	124·65	55·49	26·82	+31·82	−6·95

[a] Standard heat, standard free energy, and common logarithm of the equilibrium constant for the formation of phenol by the reaction: 6C (graphite) + $3H_2$ (g) + $\frac{1}{2}O_2$ (g) = $C_6H_5{\cdot}OH$ (g).

[14] Mecke, D.M.S. Catalogue of Infrared Spectra, Butterworths, London, Nos. 2417, 3345, 3346.
[15] Evans, *Spectrochim. Acta*, 1960, **16**, 428.
[16] Johnston, Savedoff, and Belzer, "Contributions to the Thermodynamic Functions by a Planck–Einstein Oscillator in One Degree of Freedom," Office of Naval Research, Department of the Navy, Washington, D.C., 1949.
[17] Pitzer and Gwinn, *J. Chem. Phys.*, 1942, **10**, 428.
[18] Rossini, Pitzer, Arnett, Braun, and Pimental, "Selected Values of Physical Properties of Hydrocarbons and Related Compounds," American Petroleum Institute, Research Project 44, Pittsburgh, 1953.
[19] Parks, Huffman, and Barmore, *J. Amer. Chem. Soc.*, 1933, **55**, 2733.

XUM

conjunction with the measured heat of sublimation[1] and vapour-pressure data,[1] yields as follows an observed value for the entropy of phenol at 298·16° K:

S (crystals), 0—90° K	11·72	} 34·08 ± 0·50 [19]
S (crystals), 90—298° K	22·36	
$S_{\text{sublimation}}$ (16,410 + 120)/298·16		55·04 ± 0·4 [1]
$R \ln p = R \ln (0{\cdot}3431/760)$		−15·31 [1]
Estimated correction for gas imperfection		−0·001 [1]
$S°$ (observed), 298·16° K		73·81 ± 0·64 cal./deg.mole

This is to be compared with a calculated value of $S_{\text{trans.}} + S_{\text{rot.}} + S_{\text{vib.}} + S_{\text{int.rot.}} = 39{\cdot}54 + 26{\cdot}95 + 7{\cdot}19 + 1{\cdot}77 = 75{\cdot}44 \pm 0{\cdot}20$ cal./deg.mole. The difference between the two values is probably to be attributed to error in the large contribution to the entropy from 0—90° K, which was obtained by an extrapolation method. Moreover, with the assignment given above the observed entropy requires an internal rotation contribution of 1·63 cal./deg.mole, which is equivalent to a barrier height to free rotation greater than 12,000 cal., a value which is almost certainly far too high.

Experimental.—Infrared spectra of phenol, purified in this laboratory,[1] were recorded in carbon tetrachloride and carbon disulphide solutions by using the instrument described previously.[20] The region 16—21 μ was measured on a Grubb-Parsons GS2A spectrometer by Dr. A. E. Parsons, Basic Physics Division, N.P.L.

Raman shifts to 1600 cm.$^{-1}$ of the molten samples were measured in a Hilger photoelectric Raman spectrograph with Hilger source equipment.

The author thanks Mr. W. Kynaston for experimental assistance, Drs. E. F. G. Herington and D. H. Whiffen for helpful discussion and advice, and Dr. W. H. Evans, National Bureau of Standards, Washington, for checking the calculations.

National Chemical Laboratory,
D.S.I.R., Teddington, Middlesex. [*Received, September 29th*, 1960.]

[20] Hales, *J. Sci. Inst.*, 1959, **36**, 264.

NOTES.

425. *Thermodynamic Properties of Organic Oxygen Compounds. Part III.*[1] *Formic Acid.*

By J. H. S. Green.

The thermodynamic properties of formic acid have been reviewed by Waring [2] who tabulated the functions for the monomer from 200° to 1500° K. Recent work comprises a new vibrational assignment,[3] an accurate measurement of the heat of combustion of the liquid,[4] and new values for the dimensions of the molecule determined by microwave spectroscopy.[5] Also, it is now known that the crystal has an infinite-chain type structure [6] so that the entropy does not contain a term $\frac{1}{2}R \ln 2$ arising from random orientation. A recalculation of the thermodynamic functions has therefore been made to obtain values of improved accuracy.

[1] Part II, preceding paper.
[2] Waring, *Chem. Rev.*, 1952, **51**, 171.
[3] Millikan and Pitzer, *J. Chem. Phys.*, 1957, **27**, 1305.
[4] Sinke, *J. Phys. Chem.*, 1959, **63**, 2063.
[5] Kwei and Curl, *J. Chem. Phys.*, 1960, **32**, 1592, and references therein.
[6] Holtzberg, Post, and Fankuchen, *Acta Cryst.*, 1953, **6**, 127.

XUM

The molal thermodynamic properties of formic acid monomer in the ideal-gas state.

T (°K)	$-(G° - H_0°)/T$ (cal./deg.)	$(H° - H_0°)/T$ (cal./deg.)	$(H° - H_0°)$ (kcal.)	$S°$ (cal./deg.)	$C_p°$ (cal./deg.)	$-\Delta H_f°$ (kcal.)	$-\Delta G_f°$ (kcal.)	$\log_{10} K$
200	47·381	8·155	1·621	55·536	8·963	89·96	85·87	93·83
273·16	49·987	8·546	2·324	58·532	10·304	90·36	84·44	67·56
298·16	50·732	8·714	2·598	59·446	10·807	90·49	83·89	61·49
300	50·786	8·727	2·618	59·513	10·843	90·50	83·85	61·08
400	53·401	9·509	3·804	62·910	12·845	90·96	81·56	44·56
500	55·621	10·358	5·179	65·972	14·619	91·34	79·16	34·60
600	57·576	11·197	6·718	68·773	16·019	91·63	76·70	27·94
700	59·362	11·986	8·390	71·349	17·322	91·86	74·20	23·31
800	61·011	12·719	10·175	73·729	18·345	92·04	71·65	19·57
900	62·548	13·393	12·054	75·941	19·205	92·17	69·10	16·78
1000	63·993	14·014	14·014	78·007	19·948	92·26	66·53	14·54

Values available for the individual principal moments of inertia differ somewhat, but the values for their product required for the present purpose are in satisfactory agreement; the value $6·224 \times 10^{-116}$ g.[3] cm.[6] calculated from the results of Kwei and Curl [5] was used. The symmetry number is unity and the molecular weight was taken as 46·026. The vibrational fundamentals were taken as 3570, 2943, 1770, 1387, 1229, 1105, 1033, and 636 (2) cm.$^{-1}$ and the corresponding contributions to the thermodynamic functions were obtained by using tables.[7] Fundamental constants and other values required were those used previously.[1]

From the heat of combustion of the liquid acid,[4] the heat of vaporization,[2] and the enthalpy change on passing from the saturated vapour to the ideal-gas monomer,[2] the heat of formation of the ideal-gas monomer at 298·16° K is found to be −90·49 kcal./mole. From the statistical calculations $\Delta(H° - H_0°)_f$ is −1·75 kcal./mole at 298·16° K; therefore $\Delta H_0°_f$ is −88·74 kcal./mole. The entropy for the ideal-gas monomer at 298·16° K calculated here (59·45 cal./deg. mole) is to be compared with a value 59·44 cal./deg. mole derived [2,3] from experimental data. With the present values for the ideal-gas monomer, the following revised values for the ideal-gas dimer can be derived:

T (°K)	$-\Delta H_f°$ (kcal./92·052 g.)	$S°$ (cal./92·052 g.)	$-\Delta G_f°$ (kcal./92·052 g.)
298·16	195·12	82·89	171·19
300	195·14	83·05	171·05
400	196·21	88·48	162·86

NATIONAL CHEMICAL LABORATORY,
TEDDINGTON, MIDDLESEX.

[*Received, November 4th*, 1960.]

[7] Johnston, Savedoff, and Belzer, "Contributions to the Thermodynamic Functions by a Planck-Einstein Oscillator in One Degree of Freedom," Office of Naval Research, Department of the Navy, Washington, D.C., 1949.

---

426. *Heterocyclic Compounds of Chalcone Type.*

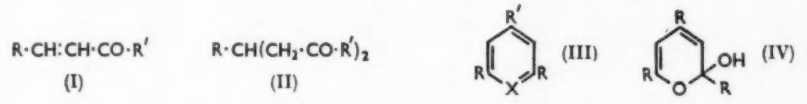
By Z. S. ARIYAN and H. SUSCHITZKY.

A NUMBER of compounds of chalcone type but containing a heterocyclic ring (I; R or R′ = heterocyclic) were prepared for biological studies. In a modification of an established method [1] ethanolic sodium hydroxide was added to a hot aqueous emulsion of the heterocyclic aldehyde and *p*-nitroacetophenone. With heterocyclic ketones as one of the reactants this procedure was satisfactory only when heating was omitted. When an excess of ketone was used and the reaction temperature was low the principal product was a Michael adduct, except in the condensation of 2-formylquinoline with acetophenone, which gave the aldol (m. p. 116°) under all conditions.[2]

Two of the Michael adducts (II; R = R′ = Ph and R = *p*-MeO·C_6H_4, R′ = Ph) were

[1] Kohler and Chadwell, *Org. Synth.*, 1922, **2**, 1.
[2] Kwartler and Lindwall, *J. Amer. Chem. Soc.*, 1937, **59**, 524.

treated with polyphosphoric acid in an attempt to cyclise them to pyrylium structures (III; X = O^+). When a solution of 1,3,5-triphenylpentane-1,5-dione (II; R = R′ = Ph)



was heated to 50° in this reagent, the mixture developed an intense green fluorescence, characteristic of the presence of pyrylium salts.[3] Neutralisation of the mixture with ammonia produced the triphenylpyridine (III; R = R′ = Ph, X = N), a result confirming the presence of a pyrylium cation which is known to be readily converted into the corresponding pyridine by ammonia or its substitution products.[4] Use of sodium hydroxide led to the triphenylpyranol (IV; R = Ph) whose infrared spectrum, in accordance with its chemical properties,[3] showed a strong carbonyl bond. Bauer[5] had obtained an unidentified substance, m. p. 137°, by the action of sodamide on the diketone (II; R = R′ = Ph); repeating this reaction we identified this compound as our triphenylpyridine. Polyphosphoric acid also proved a good cyclising agent for the preparation of the pyridine (III; R = Ph, R′ = *p*-MeO·C_6H_4, X = N).

The " chalcones " and Michael compounds showed some activity as contact poisons for the grain weevil (*Calandra granaria* L.).

TABLE 1. *Products*, R·CH:CH·CO·R′.

			Found (%)			Required (%)		Yield
R	R′	M. p.	C	H	Formula	C	H	(%)
4-Quinolyl	*p*-NO_2·C_6H_4	206°	70·9	4·0	$C_{18}H_{12}N_2O_3$	71·1	4·0	81
2-Quinolyl	,,	185·5	71·4	4·1	,,	71·1	4·0	85
2-Quinolyl	*p*-NH_2·C_6H_4	172	78·5	5·1	$C_{18}H_{14}N_2O$	78·8	5·1	74
2-Pyridyl	*p*-NO_2·C_6H_4	148·5	66·2	4·0	$C_{14}H_{10}N_2O_3$	66·1	4·2	89
4-Pyridyl	,,	216	66·5	3·6	$C_{14}H_{10}N_2O_3$	66·2	3·9	86·6
2-Furyl	,,	150	64·3	3·5	$C_{13}H_9NO_4$	64·1	3·7	89
m-NO_2·C_6H_4	2-Furyl	185	63·8	3·5	$C_{13}H_9NO_4$	64·2	3·7	92
,,	2-Thienyl	151	60·0	3·2	$C_{13}H_9NO_2S$	60·3	3·5	93
3,4-CH_2O_2·C_6H_3	*p*-NO_2·C_6H_4	210	64·6	3·7	$C_{16}H_{11}NO_5$	65·0	3·7	70
2-Quinolyl	*p*-MeO·C_6H_4	133[a]	—	—	—	—	—	69

[a] Gilman and Cason, *J. Amer. Chem. Soc.*, 1950, **72**, 3469, record m. p. 133—134°.

Experimental.—General method for preparation of chalcones. (*a*) To a vigorously stirred suspension of the appropriate aldehyde (0·1 mol.) and ketone (0·1 mol.) in water (150 ml.), heated over a small flame, about 2 ml. of 2 : 1 aqueous-ethanolic 6% sodium hydroxide solution were added. Heating was continued until a precipitate appeared. This was filtered off and yielded the *product* on recrystallisation from ethanol.

(*b*) Various *products* (I) derived from heterocyclic ketones were prepared as above, but at room temperature, and are listed in Table 1.

Preparation of Michael adducts. These *compounds* (see Table 2) were made by condensing the appropriate aldehyde (1 mol.) with the ketone (2 mol.) at room temperature under conditions described above.

Polyphosphoric acid cyclisations. (*a*) A mixture of 1,3,5-triphenylpentane-1,5-dione (1 g.) and tetraphosphoric acid (15 g.) was kept at 50° for 9 hr. with vigorous stirring. After a short time the mixture displayed an intensely green fluorescence in ultraviolet light. On pouring it into water a precipitate of 1,3,5-triphenylpyrylium phosphate was obtained. This was filtered off and triturated with aqueous ammonia, yielding 2,4,6-triphenylpyridine, m. p. 137° (from ethanol) (64%) (Found: C, 89·6; H, 5·4; N, 4·5. Calc. for $C_{23}H_{17}N$: C, 89·8; H, 5·5; N, 4·6%). Dilthey [3] reports m. p. 138·5°.

[3] Dilthey, *J. prakt. Chem.*, 1917, **95**, 107.
[4] Wislicenus and Newmann, *Annalen*, 1898, **302**, 191.
[5] Bauer, *Compt. rend.*, 1914, **158**, 1680.

XUM

TABLE 2. *Michael adducts* $R{\cdot}CH(CH_2{\cdot}CO{\cdot}R')_2$.

R	R′	M. p.	Found (%) C	Found (%) H	Formula	Required (%) C	Required (%) H	Yield (%)
4-Quinolyl	2-Naphthyl	162°	85·1	5·2	$C_{34}H_{25}NO_2$	85·2	5·3	61
4-Quinolyl	2-Thienyl	144	67·0	4·5	$C_{22}H_{17}NO_2S_2$	67·5	4·4	79
4-Quinolyl	Ph [a]	142	—	—	—	—	—	79
4-Pyridyl	Ph	120 [a]	—	—	—	—	—	87
Ph	Ph	85 [b]	—	—	—	—	—	84
3,4-CH_2O_2·C_6H_3	Ph	120	77·7	5·5	$C_{24}H_{20}O_4$	77·4	5·4	76
p-MeO·C_6H_4	Ph [c]	94	—	—	—	—	—	71

[a] Marvel, Coleman, and Scott (*J. Org. Chem.*, 1955, **20**, 1785) give m. p. 119—121°. [b,c] Kostanecki and Rossbach (*Ber.*, 1896, **29**, 1493) give (*b*) m. p. 85° and (*c*) m. p. 94 and 105°.

(*b*) When 3-*p*-methoxyphenyl-1,5-diphenylpentane-1,5-dione was treated with tetraphosphoric acid and the mixture worked up as in (*a*), 4-*p*-methoxyphenyl-2,6-diphenylpyridine, m. p. 100° (43%), was obtained (Found: C, 85·7; H, 5·7; N, 3·9. Calc. for $C_{24}H_{19}NO$: C, 85·4; H, 5·6; N, 4·1%). Dilthey *et al.*[6] record m. p. 100—101°.

We thank Mr. H. Feldman, B.Sc., of the Biology Department, the Polytechnic, Regent Street, London, for help with insecticidal experiments and Messrs. Albright and Wilson for a gift of tetraphosphoric acid.

ROYAL TECHNICAL COLLEGE, SALFORD, LANCS.
ROYAL MILITARY COLLEGE OF SCIENCE,
SHRIVENHAM, WILTS.

[*Received, October 18th*, 1960.]

[6] Dilthey *et al.*, *J. prakt. Chem.*, 1921, **102**, 209.

---

427. *Stability Constants of Some Metal Complexes of* ortho-*Aminophenols.*

By D. D. PERRIN.

STABILITY constants of metal complexes with a wide range of ligands conform to the pattern [1,2]

$$Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+} < Cu^{2+} > Zn^{2+}$$

Known exceptions, attributed to steric effects or to low-spin electronic configurations, are rare. Recently, however, the following stability constants (log K_1 at 20°, $I \sim 0{\cdot}003$) have been reported for some 1 : 1 metal complexes with 3-hydroxyanthranilic acid and *o*-aminophenol: [3]

	Mn^{2+}	Fe^{2+}	Co^{2+}	Ni^{2+}	Cu^{2+}
3-Hydroxyanthranilic acid	3·4	7·7	4·4	5·1	—
o-Aminophenol	3·6	8·0	4·7	5·4	8·8

Values for the 1 : 1 ferrous complexes are much higher than would be expected from the other members of the series. These anomalies, if real, would be of considerable theoretical interest; but, as it was also suggested [3] that oxidation of ferrous to ferric ion may have occurred, it was necessary to try to confirm these observations by repeating and extending some of the measurements, taking rigorous precautions to exclude oxygen.

This has now been done, and the results are tabulated. Stability constants, K_1 and

[1] Mellor and Maley, *Nature*, 1948, **161**, 436.
[2] Irving and Williams, *Nature*, 1948, **162**, 146; *J.*, 1953, 3192.
[3] Sims, *J.*, 1959, 3648.

β_2, for complex formation between metal ion and *o*-aminophenol anion were evaluated graphically [4] from the equation

$$K_1 = \frac{\bar{n}}{(1-\bar{n})[L^-]} - \beta_2\left(\frac{2-\bar{n}}{1-\bar{n}}\right)[L^-] \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

values of $\bar{n}$ and $[L^-]$ derived from potentiometric titrations being used. The pK_a values of the aminophenols at the ionic strengths listed in Table 2 and used in calculating the anion concentration, $[L^-]$, were obtained from Table 1 by means of the equation

$$(pK_a)_{\mu=0} = pK_a - \tfrac{1}{2}(2x-1)[I^{\frac{1}{2}}/(1+I^{\frac{1}{2}}) - 0{\cdot}20I] \quad . \quad . \quad . \quad . \quad (2)$$

for the equilibrium $H_nL^{x+} = H^+ + H_{n-1}L^{(x-1)+}$. This equation is derived from one due to Davies [5] and, except for 4-amino-5-hydroxynaphthalene-2,7-disulphonic acid and the higher pK_a of 3-amino-4-hydroxybenzenesulphonic acid, gives, in the present instance, essentially the same values as the limiting Debye–Hückel relation.

At the same ionic strengths, the present pK_a values and the results reported by Sims [3] for 3-hydroxyanthranilic acid and *o*-aminophenol agree to within 0·02 pH unit, and our stability constants, obtained under comparable conditions, for the 1 : 1 and the 1 : 2 copper complexes with *o*-aminophenol are also the same within experimental error. Our log K_1 values for the 1 : 1 ferrous complexes with 3-hydroxyanthranilic acid and *o*-aminophenol might have been expected to agree closely, except that for the latter the slight differences in ionic strength could introduce a difference of up to ~0·05. However, the present results are much lower that those previously reported and, in fact, they now fall into their predicted places in the Irving–Williams series. This sequence is also followed for the 1 : 1 complexes with 4-amino-5-hydroxynaphthalene-2,7-disulphonic acid. All the solutions containing ferrous complexes were very rapidly oxidised when air was admitted, and there seems little doubt that the previously-reported high stability constants were due to the presence of ferric ion.

In 1 : 1 metal complexes of 3-hydroxyanthranilic acid, steric requirements limit possible complex formation, so that the phenolic and carboxylic groups cannot bind simultaneously. However, there is probably little tendency for chelate ring formation involving the amino- and the carboxyl groups: when 0·01M-anthranilic acid in 0·02M-hydrochloric acid solution at 20° was titrated with alkali almost the same titration curves were obtained over the pH range 3·5—6·3 (being 1·4 pH units either side of the concentration-pK of 4·923) in the presence or absence of 0·005M-ferrous perchlorate.

For the ferrous complexes of 4-amino-5-hydroxynaphthalene-2,7-disulphonic acid, log K_2 exceeds log K_1 and is about 1—1·5 logarithmic units greater than would be expected from results for the corresponding cobalt, nickel, and copper complexes. The 1 : 2 ferrous complex of 3-hydroxyanthranilic acid also shows increased stability. If these results indicate that spin-pairing occurs in the 1 : 2 complexes, conditions must be near-borderline because neither the 2-aminophenol nor the 8-hydroxyquinoline [6] ferrous complex shows this effect.

Stability constants of the *o*-aminophenol ferric complexes could not be obtained by using an oxidation–reduction potential technique; [7] the system was unstable and potentials did not remain constant.

Experimental.—3-Hydroxyanthranilic acid was prepared and purified as described by Hegedüs.[8] 2-Aminophenol (prepared by catalytic hydrogenation of *o*-nitrophenol), 3-amino-4-hydroxybenzenesulphonic acid, and 4-amino-5-hydroxynaphthalene-2,7-disulphonic acid

[4] Irving and Rossotti, *J.*, 1953, 3397.
[5] Davies, *J.*, 1938, 2093.
[6] Albert, *Biochem. J.*, 1953, **54**, 646.
[7] Perrin, *J.*, 1958, 3120.
[8] Hegedüs, *Helv. Chim. Acta*, 1951, **34**, 611.

XUM

TABLE 1. *Dissociation constants (in terms of* pK_a*) of o-aminophenols at* 20°.

	Concn. (M)	pK_a (av. I)		$(pK_a)^*_{\mu=0}$	
o-Aminophenol (hydrochloride)	0·005	4·816 (0·005),	9·932 (0·005)	4·781,	9·967
3-Amino-4-hydroxybenzenesulphonic acid	0·005	4·096 (0·0025),	9·052 (0·0075)	4·121,	9·146
3-Hydroxyanthranilic acid	0·001	5·181 (0·0005),	10·074 (0·0015)	5·192,	10·118
4-Amino-5-hydroxynaphthalene-2,7-disulphonic acid (monosodium salt)	0·001	3·577 (0·002),	8·703 (0·0045)	3·627,	8·827

* By extrapolation, using eqn. (2).

TABLE 2. *Stability constants of metal complexes of o-aminophenols at* 20°.

	Concn. (M)	Metal, concn. (M)	Max. $\bar{n}$ *	Init. I	log K_1	log β_2
o-Aminophenol (hydrochloride)	0·005	Fe^{2+}, 0·00025	0·9	0·006	3·66	6·34
	0·005	Fe^{2+}, 0·001	0·5	0·009	3·64	
	0·001	Cu^{2+}, 0·0004	0·9	0·002	8·77	16·14
3-Amino-4-hydroxybenzenesulphonic acid	0·005	Fe^{2+}, 0·001	1·15	0·009	3·32	6·13
3-Hydroxyanthranilic acid	0·001	Fe^{2+}, 0·00025	0·75	0·002	3·8	8·3
4-Amino-5-hydroxynaphthalene-2,7-disulphonic acid (monosodium salt)	0·005	Mn^{2+}, 0·002	0·3	0·021	2·18	
	0·005	Fe^{2+}, 0·001	0·5	0·018	2·57	5·5
	0·005	Co^{2+}, 0·002	0·6	0·021	2·84	4·4
	0·005	Ni^{2+}, 0·002	1·05	0·021	3·47	5·26
	0·005	Cu^{2+}, 0·0016	2	0·020	6·91	11·15
	0·005	Zn^{2+}, 0·0005	0·2	0·016	2·45	

* Graph of $\bar{n}/(1-\bar{n})[L^-]$ against $(2-\bar{n})[L^-]/1-\bar{n})$ linear up to this value. Except for copper plus aminohydroxynaphthalenedisulphonic acid, precipitation occurred at slightly greater values of $\bar{n}$.

(monosodium salt) were purified by repeated recrystallisation from water, under nitrogen, and vacuum-dried. The metal ions were added as the perchlorates prepared by ion-exchange [9] or by double decomposition (Fe^{2+}).[7]

All pH measurements were made at 20° by using the apparatus and technique described previously,[9] except that the Perspex stopper was replaced by a tightly fitting soft rubber one. Details of titrations are summarised in the Tables. The agreement of results for *o*-aminophenol with two different concentrations of ferrous ion suggests that there was no appreciable polynuclear complex formation. Constants given to two decimal places are probably accurate to within $\pm 0{\cdot}05$. Dissociation constants have been calculated from the hydrogen-ion activity as measured by the glass electrode, the complete Henderson–Hasselbach equation being used.

DEPARTMENT OF MEDICAL CHEMISTRY,
THE AUSTRALIAN NATIONAL UNIVERSITY, CANBERRA. [*Received, October 25th*, 1960.]

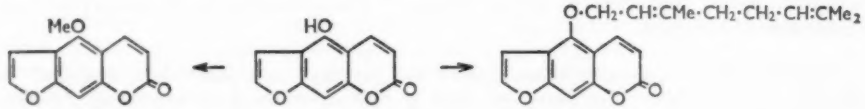
[9] Perrin, *J.*, 1960, 3189.

---

428. *The Synthesis of Bergamottin.*

By A. CHATTERJEE and (MISS) B. CHAUDHURY.

BERGAMOTTIN, 5-geranyloxypsoralene, was isolated by Späth and Kainrath [1] in 1937 from bergamot oil occurring in *Citrus bergamia* Risso (Fam. Rutaceae). Though there has



(III) (II) (I)

been little doubt that it has structure [1] (I), yet during the intervening twenty-three years no synthesis has been reported. We have now accomplished this.

[1] Späth and Kainrath, *Ber.*, 1937, **70**, 2272.

Bergaptol (II), prepared by Späth and Kubiczek's method [2] or from bergapten (III) by demethylation,[3] was refluxed for 80 hr. in alcohol with geranyl chloride [4] and sodium ethoxide, giving a 10% yield of bergamottin. The latter was isolated with great difficulty from the dark brown reaction product as, particularly when impure, it is extremely thermolabile and sensitive to acids, which caused complete resinification of the substance. A suitable procedure was, however, developed.

Experimental.—Metallic sodium (0·50 g.) was dissolved in absolute ethanol (85 ml.), and geranyl chloride (3·0 g.) and bergaptol (2·05 g.) were slowly added with cooling. The mixture was then heated under reflux for 80 hr. The solution was then cooled in ice, covered with ether (200 ml.), diluted with water (500 ml.), and shaken vigorously. Extraction with ether was repeated (3 × 50 ml.) and the total ether extract was washed with 5% aqueous alkali (3 × 30 ml.) to remove bergaptol, dried, and concentrated. The concentrate was chromatographed over Alcoa alumina, light petroleum (b. p. 60—80°) and ether being used as eluants and fractions of 25 ml. being collected. Fractions 1—8 (light petroleum, b. p. 60—80°) yielded a liquid (0·50 g.) with a smell of geraniol. Fractions 8—10 (ether) gave a semisolid mass (0·54 g.) on evaporation. This was rechromatographed over Alcoa alumina and eluted with light petroleum (b. p. 60—80°) and ether. The ether eluates afforded a colourless wax (0·46 g.) that was dissolved in light petroleum (b. p. 60—80°) (2 ml.) and kept at 0° for a few days; crystals (0·1 g.) appeared, which after several crystallisations from ethanol formed stout rods, m. p. 60° (Found: C, 74·48; H, 6·49. Calc. for $C_{21}H_{22}O_4$: C, 74·55; H, 6·5%), $\lambda_{max.}$ 220 (log ε 4·41), 250 (log ε 4·28), and 309 mμ (log ε 4·17), $\nu_{max.}$ (in Nujol) 5·82 (lactone), 6·24 (C=C), 6·33 (Ph), 7·39—7·55 (multiple peak, gem.-Me_2), 8·31 (Ph ether), 9·37 (furan), and 12·13 μ (trisubstituted double bond).

This product did not depress the m. p. of bergamottin prepared from bergamot oil, obtained through the courtesy of S. B. Pencick & Co., U.S.A., which had the same infrared and ultraviolet absorption. Our bergamottin was hydrolysed in acid, as was the natural coumarin, to bergaptol (II) and geraniol, these being respectively characterised as bergapten (III), m. p. 190°, and the allophanate, m. p. 124°. Bergaptol was also obtained from synthetic bergamottin by thermal decomposition.

The authors thank Mr. B. B. Bhattacharya, University College of Science, for microanalyses.

Department of Pure Chemistry,
University College of Science, Calcutta. [*Received, October* 31*st*, 1960.]

[2] Späth and Kubiczek, *Ber.*, 1937, **70**, 1253.
[3] Schönberg and Aziz, *J. Amer. Chem. Soc.*, 1955, **77**, 2563.
[4] Forster and Cardwell, *J.*, 1913, **103**, 1341.

---

429. *Nitromethane: Second Virial Coefficients.*

By G. A. Bottomley and I. H. Coopes.

With the type of very accurate compressibility apparatus used previously [1] for organic vapours, nitromethane (b. p. 101°) has been examined at 50°/42—95 mm. and at 67°/66—210 mm.; and gives for B^* in the equation $PV = \boldsymbol{R}T + B^*P$ [where P is the pressure (atm.), V the volume (cm.^{3}) occupied by 1 mole, and T the absolute temperature] the values of −2926 and −2317 cm.^{3}/mole respectively.

Experimental.—Material. Nitromethane was synthesised [2] from chloroacetic acid and sodium nitrite, refluxed in a stream of nitrogen, and dried over boric acid previously dehydrated in a vacuum at 200°. It was difficult to obtain nitromethane for which the Young's device [1a]

[1] (*a*) Bottomley, Reeves, and Whytlaw-Gray, *Proc. Roy. Soc.*, 1958, *A*, **246**, 504; (*b*) Bottomley and Reeves, *J.*, 1958, 3794.
[2] Vogel, "A Text-book of Practical Organic Chemistry," Longmans, Green and Co. Ltd., London, 1954, p. 306.

indicated satisfactory " de-gassing "; additional gas accumulated during storage in the " Phœnix "-glass preparation lines which were controlled solely by mercury " cut-offs."

Stability. Freshly purified nitromethane was tested in the compressibility apparatus by determining daily the pressure–volume product at constant pressure. At 50° the quantity of gas increased by some 4 parts per 100,000 per day (rather more initially, rather less after some days). The rate of increase was smaller at lower pressures and greater at 67°. No fouling of the glass or the grease-free mercury surfaces could be detected visually. Some photochemical influence was demonstrated. Excessively frequent redeterminations of the pressure–volume product definitely enhanced the volume increase.

Conduct of PV measurement. We have obtained the quoted compressibility results by following quantitatively the slight decomposition for some days, expanding the vapour to a new pressure, repeating the quantity–time determinations, and extrapolating both series of PV's to the time of expansion. The technique is otherwise as previously reported and the normal precision of 1 in 100,000 on the PV's is retained. The unknown decomposition products present to much less than 0·1% cannot significantly disturb the virial determinations.

Discussion.—Static electricity. We attribute most of the decomposition to static electricity generated by mercury movement over the dry glass surfaces both during the manipulations and inadvertently through minor vibrations in the laboratory. The instability, which corresponds to a first-order half-reaction time of about 15 years, is similar to that of carbon tetrachloride.[1b]

Adsorption. Separate determinations of the vapour adsorption on glass have been made by improved versions of the method previously described[3] and the observed PV values are appropriately corrected. The corrections for adsorption on the mercury surfaces are more difficult because of the paucity of suitable data. Cassel and Salditt[4] report for nitromethane values at 50° derived from the change in surface tension of mercury, but Kemball and Rideal[5] produce evidence that Cassel and Saldittt's mercury was contaminated by non-polar materials. We have supposed provisionally that the adsorption (moles/cm.^{2}) on the mercury is twice that on the glass as for benzene vapour. At 67° the adsorption corrections, which are the greatest uncertainty in the experiments, cannot affect the B^* value by more than ± 3 cm.^{3}/mole at most: at 50° the effects are more serious, but certainly less than ± 10 cm.^{3}/mole.

Comparison with other values. McCullough and his co-workers[6] published data on the vapour pressure, latent heat of vaporisation, and vapour heat-capacity of nitromethane which Douslin and Waddington[7] correlated by means of a Stockmayer intermolecular potential. For comparison with Douslin and Waddington's work we have re-cast our results in terms of $PV = \boldsymbol{RT} + B/V$, which makes $B = -2866$ (50°) and -2247 (67°) cm.^{3}/mole. We have used a $\log_{10} B$–$1/T$ plot (which is linear except at the lowest temperature) to interpolate their virial coefficient values to our temperatures and estimate that our B values are less negative by 2·2% (50°) and 1·3% (67°).

The extremely high non-ideality of nitromethane vapour and other physical properties, which are often attributed to association, make desirable a careful examination of the PV–P curve for indications of abnormal non-linearity. It is most regrettable that the observed instability hinders this work.

Department of Chemistry, The University of Western Australia,
Nedlands, Western Australia. [*Received, November 21st,* 1960.]

[3] Bottomley and Reeves, *Trans. Faraday Soc.*, 1957, **53**, 1455.
[4] Cassel and Salditt, *Z. phys. Chem.* (*Leipzig*), 1931, **155**, 321.
[5] Kemball and Rideal, *Proc. Roy. Soc.*, 1946, *A*, **187**, 53.
[6] McCullough, Scott, Pennington, Hossenlopp, and Waddington, *J. Amer. Chem. Soc.*, 1954, **76**, 4791.
[7] Douslin and Waddington, *J. Chem. Phys.*, 1955, **23**, 2453.

XUM

430. *A New Stereospecific Reaction.*

By H. Irving and R. D. Gillard.

It has been shown that the following reactions between (*a*) complexes of ethylenediaminetetra-acetic acid (edta) or (+)-propylenediaminetetra-acetic acid, $A_2N{\cdot}CHMe{\cdot}CH_2{\cdot}NA_2$ (pdta; A = $CH_2{\cdot}CO_2H$) with cobalt(III), and (*b*) ethylenediamine (en) or (±)-propylenediamine (pn), occur with increasing retention of configuration: *

(+)-[Co(edta)]$^-$ + en = (+)-[Co(en)$_3$]$^{3+}$ + edta (ref. 1)
(+)-[Co(edta)]$^-$ + (±)-pn = (+)-[Co(+-pn)$_3$]$^{3+}$ + edta (ref. 2)
(−)-[Co(+-pdta)]$^-$ + (±)-pn = (+)-[Co(+-pn)$_3$]$^{3+}$ + (+)-pdta (ref. 3)

It has now been shown that the reaction:

(−)-[Co(+-pdta)]$^-$ + en = (+)-[Co(en$_3$)]$^{3+}$ + (+)-pdta

proceeds at 25° with a retention of configuration comparable with that of reaction (2) above: the pdta displaced from the complex anion retains its full optical activity.

Experimental.—Ethylenediamine (0·8 g., 0·0132 mole) in water (3 ml.) was added to a solution of lævorotatory potassium (+)-1,2-propylenediaminetetra-acetatocobalt(III) trihydrate (1 g., 0·0022 mole) in water (5 ml.) at 20°. During 12 min. at 25·0° the originally deep purple mixture became orange. After a further 15 min. sodium iodide (1 g.) in water (1 ml.) was added and the whole poured into ice-cold acetone (150 ml.). A viscous orange mass (A) separated and the mother-liquor (B) was removed by decantation. The product (A) was taken up in water (2 ml.) and poured into ice-cold acetone (100 ml.); a viscous orange material again separated. After removal of the supernatant liquid this was thoroughly cooled; scratching then caused separation of dextrorotatory trisethylenediamminocobalt(III) iodide trihydrate as a yellow powder (1·33 g., 90%) (Found: Co, 8·7. Calc. for $C_6H_{24}N_6I_3,3H_2O$: Co, 8·74%). In water $[M]_D^{20}$ = +537°. Werner [4] gives +602·5° and +552·5° for the corresponding bromide and chloride.

The acetone mother-liquors (B) were concentrated to 30 ml. on a water-bath, acidified to pH 2 with dilute hydrochloric acid, and passed through a column of cation-exchange resin (ZeoKarb 225, H^+ form). The effluent was concentrated to 5 ml. and strongly cooled; scratching caused the separation of (+)-pdta monohydrate as a white powder (0·55 g., 77%) with $[\alpha]_D^{20}$ +46°. Dwyer and Garvan [5] report +47°. After being dried at 130° the anhydrous material had m. p. 193° and $[\alpha]_D^{20}$ +50°. Dwyer and Garvan [5] report m. p. 194° and the same rotation.

We thank Mr. Ridley for the polarimetric measurements.

Inorganic Chemistry Laboratory, Oxford. [*Received, November 21st,* 1960.]

* (+) and (−) outside the square bracket refer to the whole ion.

[1] Dywer, Gyarfas, and Mellor, *J. Phys. Chem.*, 1955, **59**, 296.
[2] Bailar, Kirschner, and Yung Kang Wei, *J. Amer. Chem. Soc.*, 1957, **79**, 5877.
[3] Irving and Gillard, *J.*, 1960, 5266.
[4] Werner, *Ber.*, 1912, **45**, 124.
[5] Dwyer and Garvan, *J. Amer. Chem. Soc.*, 1959, **81**, 2955.

431. 10-*Methylphenanthridine.*

By M. S. Gibson.

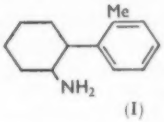
10-Methylphenanthridine, whose picrate was required as a reference compound, has been prepared by application of the Diels–Alder and Bischler–Napieralski reactions.

o-Tolualdehyde was condensed with nitromethane to give 2-methyl-ω-nitrostyrene. The Diels–Alder adduct [1] from the latter and butadiene was then hydrogenated to the

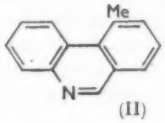
[1] Cf. Allen, Bell, and Gates, *J. Org. Chem.*, 1943, **8**, 373.

XUM

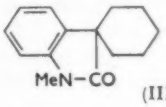
intermediate cyclohexylamine (I). Formylation and dehydration gave 1,2,3,4,4a,10b-hexahydro-10-methylphenanthridine (*ca.* 5% yield), which was dehydrogenated by selenium [2] to the phenanthridine (II), which was isolated as the picrate.



(I)



(II)



(III)

The oxindole (III) has been prepared from cyclohexanecarboxylic acid and *N*-methyl-*N*-phenylhydrazine by Brunner's method.[3] The speculation that distillation with zinc dust might yield phenanthridine was not realized; nor did dehydrogenation give basic products.

Experimental.—*2-Methyl-ω-nitrostyrene.* Sodium hydroxide (7 g.) in water (18 ml.) was added dropwise to a stirred solution of *o*-tolualdehyde (20 g.) and nitromethane (10 g.) in methanol (35 ml.), the mixture being kept at 10—15°. As the mixture became pasty, methanol (15 ml.) was added. Stirring was continued for a further 15 min., and then ice and water (*ca.* 300 g.) were added. The resulting solution was added to 14% hydrochloric acid (90 ml.), a yellow oil separating. Ether-extraction, drying, and distillation gave *2-methyl-ω-nitrostyrene* (19 g.), b. p. 150—151°/13 mm., n_D^{14} 1·6276 (Found: C, 66·3; H, 5·5; N, 8·7. $C_9H_9NO_2$ requires C, 66·3; H, 5·5; N, 8·6%).

4-Nitro-5-o-tolylcyclohexene. A mixture of 2-methyl-ω-nitrostyrene (17 g.), butadiene (10 g.), and toluene (24 ml.) was heated in an autoclave for 5 hr. at 150°. Evaporation *in vacuo* gave a dark oil, which solidified on trituration with light petroleum. Crystallisation from aqueous methanol (charcoal) gave *4-nitro-5-o-tolylcyclohexene* (16 g.) as brownish needles, m. p. 65—71°, raised after two further crystallisations to 79—80° (Found: C, 72·2; H, 7·15; N, 6·25. $C_{13}H_{15}NO_2$ requires C, 71·9; H, 6·9; N, 6·45%).

4-Methyl-ω-nitrostyrene [4] (3·1 g.) similarly gave *4-nitro-5-p-tolylcyclohexene* (2·8 g.; 1·8 g. after four crystallisations with charcoal), which formed elongated plates, m. p. 84—86°, from aqueous methanol (Found: C, 71·6; H, 7·0; N, 6·5%).

2-o-Tolylcyclohexylamine. 4-Nitro-5-*o*-tolylcyclohexene (10 g.) was hydrogenated in warm ethanol over Raney nickel at atmospheric pressure (absorption 4·27 l.). The catalyst was filtered off, and the filtrate concentrated *in vacuo*. The resulting oil was dissolved in dry benzene and saturated with dry hydrogen chloride. Evaporation *in vacuo* gave a gummy solid. This was leached with boiling water (charcoal), and the filtrate was basified and extracted with ether. Drying and saturation with dry hydrogen chloride precipitated the *hydrochloride* as a colourless solid. The salt (7·8 g.) separated from ether–ethanol as prisms, m. p. 228—229° (Found: C, 69·4; H, 8·8; N, 6·5. $C_{13}H_{20}NCl$ requires C, 69·2; H, 8·9; N, 6·2%). Addition of aqueous sodium nitroprusside solution, followed by a few drops of sodium carbonate solution, to the hydrochloride in aqueous acetone, produces a plum-red colour which slowly becomes purple.

1,2,3,4,4a,10b-Hexahydro-10-methylphenanthridine picrate. 2-*o*-Tolylcyclohexylamine (from 7·5 g. of hydrochloride) was heated with 98—100% formic acid (2·5 ml.) at 150° for 5 hr. in an open flask. The crude formyl derivative was dissolved in purified tetralin (125 ml.), and phosphoric anhydride (18 g.) was added to the boiling solution during 40 min. The tetralin was then decanted, and the brown residue was washed with ether and extracted with hot aqueous hydrochloric acid (charcoal). The acidic filtrate was washed with ether, basified, and the resulting suspension extracted with ether. Treatment of the dried ether extract with dry hydrogen chloride yielded a brown gum. This was dissolved in boiling water (charcoal), and the filtrate was basified and extracted with ether. Addition of ethanolic picric acid to the dried ether solution precipitated the *hexahydromethylphenanthridine picrate* (620 mg.). Three crystallisations from aqueous ethanol gave yellow needles, m. p. 172—173° (Found: C, 56·2; H, 4·4; N, 13·4. $C_{20}H_{20}N_4O_7$ requires C, 55·9; H, 4·7; N, 13·1%).

[2] Cf. Braude and Fawcett, *J.*, 1951, 3113.
[3] Cf. Moore and Plant, *J.*, 1951, 3475.
[4] Worrall, *J. Amer. Chem. Soc.*, 1938, **60**, 2841.

10-*Methylphenanthridine picrate*. The hexahydrophenanthridine (from 200 mg. of picrate) was heated with powdered selenium (140 mg.) at 360° for 6 hr. The dark residue was extracted with hot dilute hydrochloric acid (charcoal), and the filtrate was basified and extracted with ether. Ethanolic picric acid precipitated 10-*methylphenanthridine picrate* (65 mg.) from the dried solution. The salt separated from acetone as yellow prisms, m. p. 204—206° (Found: C, 56·5; H, 3·6; N, 13·0. $C_{20}H_{14}N_4O_7$ requires C, 56·9; H, 3·3; N, 13·3%). The free base was not characterised.

Attempted dehydrogenation at 330° with selenium led only to recovery of a small amount of the hexahydrophenanthridine picrate.

1-*Methyloxindole*-3-*spirocyclohexane*. A mixture of *N*-methyl-*N*-phenylhydrazine (5 g.) and cyclohexanecarboxylic acid [5] (5 g.) was heated at 165° for 3 hr., then poured into water; the *hydrazide* that separated crystallised from aqueous ethanol as needles, (8 g.), m. p. 141—142° (Found: C, 72·6; H, 8·8; N, 11·8. $C_{14}H_{20}N_2O$ requires C, 72·4; H, 8·6; N, 12·1%).

A mixture of the hydrazide (7·5 g.) with freshly baked calcium oxide (22·5 g.) was heated at 250—280° until evolution of ammonia slackened (3—4 hr.). The cooled mixture was treated with an excess of 20% hydrochloric acid, much tar separating. After 30 minutes' boiling, the mixture was cooled and extracted with ether. The *spiran* (2 g.) was obtained as a pale yellow gum, b. p. 180—182°/19 mm. (Found: C, 77·8; H, 7·8; N, 6·7. $C_{14}H_{17}ON$ requires C, 78·1; H, 7·9; N, 6·5%). It gives an intense magenta colour with concentrated sulphuric acid and a crystal of sodium dichromate.

Bromination in acetic acid gave (probably) the 5,7-*dibromo-derivative*, which crystallised from aqueous ethanol in needles, m. p. 136—137° (Found: C, 45·0; H, 3·9. $C_{14}H_{15}ONBr_2$ requires C, 45·0; H, 4·0%).

The parent oxindole distilled unchanged from zinc dust at 280—300°; dehydrogenation with sulphur produced carbonaceous material from which no basic product could be isolated.

The author thanks Sir Robert Robinson, F.R.S., for his interest, and the Department of Scientific and Industrial Research for a maintenance grant.

Dyson Perrins Laboratory, Oxford.
[Present address: Chemistry Department, The University, Manchester, 13.] [*Received, November 25th*, 1960.]

[5] Sabatier and Mailhe, *Ann. Chim.* (*France*), 1907, **10**, 527.

---

432. *Applications of the "Abnormal" Reimer–Tiemann Reaction.*

By M. S. Gibson.

Details of experiments which were to serve as a model for a synthesis of ferruginol are now reported.

Reaction of 4-methyl-1-naphthol with chloroform and alkali (dichlorocarbene) has been shown [1,2,3] to give 1-dichloromethyl-1,4-dihydro-1-methyl-4-oxonaphthalene. The isomeric 2-methyl-1-naphthol similarly gives [1,4,5] 1-dichloromethyl-1,2-dihydro-1-methyl-2-oxonaphthalene, though in much better yield. For the purpose of the model, 1,2,3,4-tetrahydro-1,1-dimethylphenanthr-9-ol was prepared from ethyl γ-(4-methoxy-1-naphthyl)-butyrate by reaction with methylmagnesium iodide, dehydration of the intermediate

[1] Gibson, *Experientia*, 1951, **7**, 176.
[2] Fuson and Miller, *J. Org. Chem.*, 1952, **17**, 316.
[3] Wenkert and Stephens, *J. Amer. Chem. Soc.*, 1956, **78**, 5627.
[4] Bell and Hunter, *J.*, 1950, 2903.
[5] Dodson and Webb, *J. Amer. Chem. Soc.*, 1951, **73**, 2767.

Vol. 1961, page 2251, line 4 *. *For* 2-methyl-1-naphthol *read* 1-methyl-2-naphthol.

XUM

alcohol, cyclisation to the tetrahydrophenanthrene, and demethylation with hydriodic acid. This phenol reacted with dichlorocarbene to yield only the " abnormal " product:

it seems that the 1-methyl groups exert greater hindrance at position 10 than at position 4a, and the latter is thus the preferred site of attack by dichlorocarbene.

This result is interesting since the " abnormal " Reimer–Tiemann reaction has been successfully applied to *ar*-β-[6] and *ar*-α-tetralol,[7] but failed when applied to various steroid analogues (*e.g.*, œstrone), evidently because of the steric interference by axial 8-, 9-, and 11-hydrogen atoms with attack by dichlorocarbene at positions 10 and 13.

Experimental.—Most of the analyses were by Mr. F. C. Hall; ultraviolet spectra were measured for ethanol solution by Mr. F. Hastings.

Ethyl γ-(4-methoxy-1-naphthyl)butyrate.[8] A solution of γ-(4-methoxy-1-naphthyl)butyric acid [9] (20 g.) in ethanol (275 ml.) and concentrated sulphuric acid (12 ml.) was refluxed for 14 hr., giving, in the usual way, the *ethyl ester* (15 g.), b. p. 167—170°/0·18 mm., n_D^{16} 1·5703 (Found: C, 75·3; H, 7·5. $C_{17}H_{20}O_3$ requires C, 75·0; H, 7·4%).

2-Methyl-5-(4-methoxy-1-naphthyl)pentan-2-ol and dehydration thereof. Ethyl γ-(4-methoxy-1-naphthyl)butyrate (14 g.) in dry ether (50 ml.) was added during 30 min. to a boiling solution of methylmagnesium iodide (from 5 g. of magnesium) in ether (65 ml.). Boiling was continued for 6 hr. After being kept overnight, the mixture was decomposed with ice and sulphuric acid, and extracted with ether. Washing with sodium hydrogen carbonate solution and water, drying, and evaporation gave the crude alcohol as a yellow oil. Distillation gave a mixture of alcohol and olefin(s) (11 g.), collected at 129—144°/0·04 mm. (Found: C, 83·0; H, 8·6%).

The mixture (10·5 g.) was heated with anhydrous copper sulphate (3 g.) at 150—160° until no more water was evolved (1—2 hr.). When cool, water was added, and the product was isolated with ether. Distillation gave mixed 2-methyl-5-(4-methoxy-1-naphthyl)pentenes (9·5 g.), b. p. 132—137°/0·03 mm., n_D^{16} 1·5914 (Found: C, 84·9; H, 8·3. Calc. for $C_{17}H_{20}O$: C, 85·0; H, 8·3%).

On hydrogenation in acetic acid with palladised charcoal the olefins (248 mg.) absorbed 24 ml. of gas at 17°/760 mm. (0·98 double bond).

The olefins decolorised alkaline potassium permanganate solution immediately.

1,2,3,4-Tetrahydro-9-methoxy-1,1-dimethylphenanthrene. A solution of the olefins (7 g.) in dry chloroform (70 ml.) was saturated with dry boron trifluoride with ice-cooling. After 30 min., the brown solution was allowed to warm to room temperature (10—15 min.) and then poured into an excess of sodium acetate solution with stirring. The chloroform extract was washed, dried, and distilled to yield the *phenanthrene* (6 g.), b. p. 150—170° (bath)/0·06 mm. The re-distilled compound solidified on trituration with light petroleum, and separated from ether as colourless rhombs, m. p. 59° (Found: C, 84·8; H, 8·4. $C_{17}H_{20}O$ requires C, 85·0; H, 8·3%).

The product was not hydrogenated under the above conditions; nor did it decolorise potassium permanganate solution.

In a separate experiment, 100% phosphoric acid at 100° for 8 hr. effected only 30% cyclisation (calc. from hydrogenation results).

1,2,3,4-Tetrahydro-1,1-dimethylphenanthr-9-ol. A solution of 1,2,3,4-tetrahydro-9-methoxy-1,1-dimethylphenanthrene (5 g.) in acetic acid (60 ml.) and freshly distilled hydriodic acid (25 ml.; *d* 1·7) was heated at 120—130° under carbon dioxide for 3 hr. The cooled mixture was poured into water, neutralised with sodium carbonate solution, and decolorised with sodium dithionite. The precipitated *1,2,3,4-tetrahydro-1,1-dimethylphenanthr-9-ol* (4·5 g.) was collected, washed

[6] Woodward, *J. Amer. Chem. Soc.*, 1940, **62**, 1208.
[7] Wynberg and Johnson, *J. Org. Chem.*, 1959, **24**, 1424.
[8] Cf. Burtner, U.S.P. 2,590,086/1952.
[9] Martin, *J. Amer. Chem. Soc.*, 1936, **58**, 1438.

and dried. Crystallisation from cyclohexane gave prisms, m. p. 139° (Found: C, 84·7; H, 8·2. $C_{16}H_{18}O$ requires C, 84·95; H, 8·0%).

4a-*Dichloromethyl*-1,2,3,4,4a,9-*hexahydro*-1,1-*dimethyl*-9-*oxophenanthrene*. Chloroform (10 g.) was added during 3 hr. to a solution of 1,2,3,4-tetrahydro-1,1-dimethylphenanthr-9-ol (3·8 g.) in 10% aqueous sodium hydroxide (60 ml.) kept under reflux at 75°. After a further hour, the mixture was cooled, slightly acidified, and extracted with chloroform. The extract was washed with sodium hydroxide solution and water, dried, and evaporated. The residue was adsorbed on alumina from benzene–light petroleum solution; elution with benzene gave yellowish, slightly gummy fractions, which were collected in ethanol. Evaporation to small bulk and chilling gave 4a-*dichloromethyl*-1,2,3,4,4a,9-*hexahydro*-1,1-*dimethyl*-9-*oxophenanthrene* (0·5 g.), which separated from cyclohexane as plates, m. p. 124° (Found: C, 66·6; H, 5·8; Cl, 23·15. $C_{17}H_{18}Cl_2O$ requires C, 66·0; H, 5·8; Cl, 23·0%), $\lambda_{max.}$ 255 (log ε 4·06) and (sh) 279 mμ (log ε 3·91), $\lambda_{infl.}$ 270 mμ (log ε 3·96).

The alkaline washings from the extraction were acidified and extracted with chloroform. Evaporation and chromatography on silica gave starting material (0·5 g.; eluted with benzene).

1-*Dichloromethyl*-1,4-*dihydro*-1-*methyl*-4-*oxonaphthalene*. In like manner, 4-methyl-1-naphthol [10] (2 g.) gave the dichloro-ketone (0·4 g.), isolated chromatographically from neutral products. The compound separated from cyclohexane in needles, m. p. 106—107° (Found: C, 59·8; H, 4·4; Cl, 29·4. Calc. for $C_{12}H_{10}Cl_2O$: C, 59·8; H, 4·2; Cl, 29·45%), $\lambda_{max.}$ 231 (log ε 3·98) and 263 mμ (log ε 3·84), $\lambda_{min.}$ 251 mμ (log ε 3·82).

1-*Dichloromethyl*-1,2-*dihydro*-1-*methyl*-2-*oxonaphthalene*. 1-Methyl-2-naphthol (2 g.) similarly reacted with chloroform and sodium hydroxide. Chromatography of neutral products on alumina and crystallisation from light petroleum (b. p. 40—60°) gave the dichloro-ketone (2 g.) as blades, m. p. 66—67° (Found: C, 60·0; H, 4·3; Cl, 29·2. Calc. for $C_{12}H_{10}Cl_2O$: C, 58·8; H, 4·2; Cl, 29·45%), $\lambda_{max.}$ 237 (log ε 4·11) and 313 mμ (log ε 3·98), $\lambda_{min.}$ 257 mμ (log ε 2·68).

The author thanks Dr. J. A. Barltrop for his interest and advice, and the Ministry of Education for a maintenance grant.

Dyson Perrins Laboratory, Oxford.
Chemistry Department,
The University, Manchester, 13. [*Received, December 6th*, 1960.]

[10] Elbs and Christ, *J. prakt. Chem.*, 1923, **106**, 17.

---

433. 3-*Nitro*-2-*naphthoic Acid*.

By R. D. Topsom and J. Vaughan.

Berliner and Winicor [1] measured the dissociation constants of thirteen mononitronaphthoic acids at 25° in 50% aqueous "butyl cellosolve" (2-butoxyethanol). The remaining member of this series (3-nitro-2-naphthoic acid) could not then be prepared. This acid has now been made from 3-amino-2-naphthoic acid, *via* the diazonium sulphate, the simplified technique of Ward, Johnson, and Hawkins [2] being used. Preparation from the amino-ester was unsatisfactory because extraction of the product was difficult, and attempts to make the required acid through the diazonium fluoroborate were unsuccessful.

The pK of the acid, determined under Berliner's conditions, was 4·89 and that of 2-naphthoic acid 5·97. The difference (1·08) is smaller than that for the 1-nitro-acid ($\Delta pK = 1·42$) and is greater than that for the 4-nitro-acid ($\Delta pK = 0·98$).[1] The acidity of 3-nitro-2-naphthoic acid is thus approximately that which would be predicted following Berliner and Winicor's discussion.

Experimental.—3-*Nitro*-2-*naphthoic acid*. To a paste of 3-amino-2-naphthoic acid (7·5 g.) with water (20 ml.) were added sulphuric acid (8 ml.), water (20 ml.), and crushed ice (40 g.). Sodium nitrite solution (4·0 g. in 10 ml.) was added to the stirred mixture and stirring continued

[1] Berliner and Winicor, *J. Amer. Chem. Soc.*, 1959, **81**, 1630.
[2] Ward, Johnson, and Hawkins, *J.*, 1960, 894.

XUM

for 5 min. The mixture was then added to a hot, stirred mixture of sodium nitrate (150 g.), hydrated copper sulphate (20 g.), cuprous oxide (12 g.), and sodium hydrogen carbonate (40 g.) in water (400 ml.). Much gas was evolved and stirring was continued for 1 hr. The precipitate was filtered off and washed with saturated sodium hydrogen carbonate solution (3 × 50 ml.). The combined filtrates were cooled and carefully acidified (to pH 5) with dilute sulphuric acid before being extracted with ether (250 ml.). Addition of acid and extraction with ether were carried out twice more. The total ethereal extract was then washed twice with water and extracted with sodium hydroxide solution until colour was no longer removed. Addition of acid precipitated the crude *3-nitro-2-naphthoic acid*, m. p. 211—214°, as a pale yellow solid (2·2 g.; 25% theory). The acid was purified chromatographically on alumina, ethanol being used as solvent and ethanol : water (1 : 3) as eluent. Recrystallisation from dilute ethanol gave white crystals m. p. 220·5° (Found: C, 60·9; H, 3·2; N, 6·0, 6·6. $C_{11}H_7O_4N$ requires C, 60·8; H, 3·2; N, 6·45%).

Dissociation constant. Berliner and Winicor's method was followed, a Cambridge portable pH meter being used. The purified butyl cellosolve (2-butoxyethanol) boiled at 170·5—171°/764 mm. Two determinations gave the pK of 3-nitro-2-naphthoic acid as 4·90 and 4·87. Compatibility with Berliner's results was checked with 2-naphthoic acid (pK 5·95, 5·98; in agreement with Berliner's figure, 5·95).

We thank Dr. A. D. Campbell, University of Otago, for the microanalyses.

UNIVERSITY OF CANTERBURY,
CHRISTCHURCH, NEW ZEALAND. [*Received, November 28th*, 1960.]

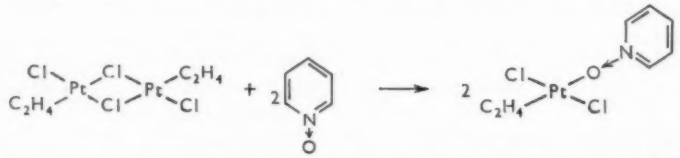
---

434. *Ethylene-platinous Chloride Pyridine N-Oxide.*

By LEONARDO GARCIA and MILTON ORCHIN.

ANDERSON has reported[1] that treatment of ethylene-platinous chloride (di-μ-chloro-dichlorodiethylenediplatinum) with an excess of pyridine results in complete displacement of all the ligands and the formation of a salt $[Pt(C_5H_5N)_4]Cl_2$. In connexion with the studies[2] on the relative strength of ligand bonding in platinum(II)–olefin complexes, a variety of pyridine compounds have been investigated.

When an aqueous solution of Zeise's salt ($K[C_2H_4PtCl_3]$) is treated with 1—4 mol., or with a large excess, of pyridine 1-oxide, the same stable compound separated on storage at room temperature; it recrystallized from chloroform as green needles, m. p. 145—146° (decomp.). The identical compound (infrared spectrum, ultimate analysis, m. p., and appearance) was secured on treatment of the non-ionic dimeric ethylene-platinous chloride $[C_2H_4PtCl_2]_2$ in ethanol with pyridine 1-oxide. In neither of the platinum complex reactions with pyridine oxide was gas evolved, and the spectrum of the product showed an absorption peak at 3000 cm.$^{-1}$ characteristic of the olefinic C–H stretching mode. Analysis of the green *compound* [Found, for material from the dimeric complex: C, 21·8;



H, 2·6; N, 3·6. Found, for material from Zeise's salt: C, 22·0; H, 2·4; N, 3·6. $(C_2H_4)PtCl_2(C_5H_5NO)$ requires C, 21·6; H, 2·3; N, 3·6%] indicates that both reactions involve straight-forward displacements which, in the case of the dimeric complex, can be written as illustrated. A similar reaction with Zeise's salt can be written, but then chloride ion is liberated.

[1] Anderson, *J.*, 1934, 1971.
[2] Joy and Orchin, *J. Amer. Chem. Soc.*, 1959, **81**, 305, 310.

Although there is no unequivocal evidence that the pyridine oxide takes up the position *trans* to ethylene, it is reasonable to expect this disposition because of the *trans*-activating effect of the unsaturated ligand. The failure to incorporate more than one pyridine oxide molecule is probably due to the weaker basicity of the oxide (pK 0·79) than of the parent pyridine [3] (pK 5·29), although there is usually little correlation between the basicity of a ligand and its tendency to form platinum complexes.

We thank the Engelhard Industries, Inc., for a generous supply of platinum.

UNIVERSITY OF CINCINATTI,
CINCINATTI, OHIO, U.S.A

[*Received, November 10th,* 1960.]

[3] Jaffé and Doak, *J. Amer. Chem. Soc.*, 1955, **77**, 4441.

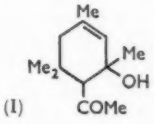
---

435. *Reaction Products from Mesityl Oxide and Lithium.*

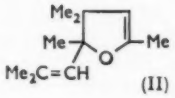
By N. BACON, S. BREWIS, G. E. USHER, and E. S. WAIGHT.

MESITYL OXIDE undergoes an exothermic reaction in the presence of lithium, to give a complex mixture from which the solid dimer (I) is readily isolated.[1] We now report on the nature of the liquid products.

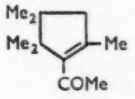
One component ($C_{12}H_{20}O$) is readily separable by distillation. Its infrared spectrum is very similar to that reported by Nahum [2] for the cyclic vinyl ether (II) obtained in the reduction of mesityl oxide with sodium amalgam. The nuclear magnetic resonance spectrum is consistent with this structure. An ether of this structure has also been obtained by the action of magnesium and acetic acid on mesityl oxide,[3] and we have shown that its infrared and nuclear magnetic resonance spectra are identical with those of the ether from the lithium reaction.



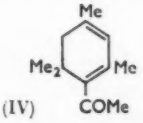
(I)



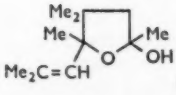
(II)



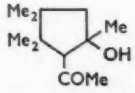
(III)



(IV)



(V)



(VI)

A second pure component can be obtained through its semicarbazone. Its infrared spectrum is almost identical with that of 2-acetyl-1,3,3,4,4-pentamethylcyclopentene (III) reported by Nahum,[2] and this structure is supported by the nuclear magnetic resonance spectrum. This ketone is also formed in the reduction with magnesium and acetic acid.

The high-boiling residue left on removal of these three compounds contains a conjugated dienone which has not been obtained pure. From the melting point and ultraviolet light absorption of its 2,4-dinitrophenylhydrazone it is probably the " isoxylitone " formulated as (IV) by Wiemann and his co-workers.[4]

The reaction of mesityl oxide with lithium thus gives products arising by base-catalysed dimerization, with and without dehydration, and by bimolecular reduction with dehydration. It is probable that compounds (II) and (III) are formed directly

[1] Braude, Gofton, Lowe, and Waight, *J.*, 1956, 4054.
[2] Nahum, *Ann. Chim.* (*France*), 1958, **3**, 108.
[3] Kolobielski, *Ann. Chim.* (*France*), 1955, **10**, 271.
[4] Wiemann, Sa-Le Thi-Thuan, and Conia, *Bull. Soc. chim. France*, 1957, 908; Wiemann, Furth, and Dana, *Compt. rend.*, 1960, **250**, 3674.

and not by dehydration of intermediates (V) and (VI), since significant amounts of these two alcohols cannot be detected, as they can be on bimolecular reduction with sodium amalgam or magnesium.

Experimental.—Microanalyses are by Miss J. Cuckney and the staff of the Organic Microanalytical Laboratory. Infrared spectra of liquid films were determined by Dr. R. L. Erskine and Mrs. A. I. Boston using a Grubb–Parsons S4 double-beam spectrometer. Nuclear magnetic resonance spectra of solutions in carbon tetrachloride were measured by Drs. L. M. Jackman and J. W. Lown using a Varian 4300 spectrometer, and are expressed as τ-values.[5]

Reaction of mesityl oxide and lithium. Procedure (*b*) described by Braude *et al.*[1] was used. The product (165 g.), b. p. 48—103°/3·5 mm. (from mesityl oxide, 250 g.), was freed from solid dimer (32 g.) and redistilled through a 2 ft. Stedman column.

2,3-*Dihydro*-2,3,3,5-*tetramethyl*-2-2′-*methylpropenylfuran* (II). This was the major (>95%) component of the fraction (9 g.) of b. p. 47°/0·9 mm., n_D^{26} 1·4570 (Found: C, 79·9; H, 11·1. Calc. for $C_{12}H_{20}O$: C, 79·9; H, 11·2%), $\nu_{max.}$ 3065w (=C–H), 1670s (C=C–O), 1067s, 1055s, 960s, 738s cm.$^{-1}$. Nuclear magnetic resonance (of italicized protons): 9·11, 9·00 [$>C(CH_3)_2$]; 9·03 (trace, impurity); 8·80 [$>C(CH_3)\cdot O\cdot$]; 8·32, 8·29, 8·27 [$C(CH_3)_2$=CH]; 8·20, 8·17 [O·C(CH_3)=CH]; 5·71 (C*H*=C–O); 4·91 (C*H*=C<) p.p.m. Gas–liquid chromatography indicated the presence of a trace of a less volatile impurity which could not be removed by distillation or chromatography.

2-*Acetyl*-1,3,3,4,4-*pentamethylcyclopentene* (III). The fraction, b. p. 62—78°/4 mm. (53 g.), was treated with aqueous semicarbazide acetate. The bulk failed to react and was recovered (41 g.); it had b. p. 100—165°/2 mm., n_D^{26} 1·503—1·509. The semicarbazone, m. p. 170—171° (from ethanol) (Kolobielski [3] gives m. p. 166—166·5°), was hydrolysed by hot 0·5N-sulphuric acid, and the ketone extracted with ether. It had b. p. 70°/1 mm., n_D^{23} 1·4743, $\lambda_{max.}$ 252 mμ (ε 7900 in EtOH), $\nu_{max.}$ 1667vs (C=O), 1619m (C=C) cm.$^{-1}$. Nuclear magnetic resonance (for italicized protons): 9·12 [$>C(CH_3)_2$]; 9·04 [$>C(CH_3)_2$]; 8·11, 8·08, 8·05 [–C(CH_3)=C<]; *ca.* 7·85 ($>CH_2$); 7·80 [$C(CH_3)$=O] p.p.m. The ketone gave a red 2,4-dinitrophenylhydrazone, m. p. 125·5—126·5° (from methanol) (Found: C, 59·9; H, 6·7; N, 15·6. Calc. for $C_{18}H_{24}N_4O_4$: C, 60·0; H, 6·7; N, 15·5%).

"*Isoxylitone*." The residue, b. p. >103°/3·5 mm., was freed from further amounts of solid dimer and after redistillation had $\lambda_{max.}$ 237, 296 mμ ($E^{1\%}_{1\,cm.}$ 129, 270). It afforded a dark red 2,4-dinitrophenylhydrazone, which after chromatography on bentonite–kieselguhr and crystallization from methanol had m. p. 159—160° (Found: N, 15·7. Calc. for $C_{18}H_{22}N_4O_4$: N, 15·6%), $\lambda_{max.}$ 408 mμ (ε 22,600 in chloroform). Wiemann *et al.*[4] give for 1-acetyl-2,4,6,6-tetramethylcyclohexa-1,3-diene $\lambda_{max.}$ 235, 291 mμ (ε 4000, 13,000) and for its 2,4-dinitrophenylhydrazone m. p. 156°, $\lambda_{max.}$ 406 mμ (ε 24,000).

Bimolecular reduction of mesityl oxide.[3] To a stirred mixture of mesityl oxide (25 g.), acetone (63 ml.), water (28 ml.), and magnesium (10 g.) at −25° to −30° 90% aqueous acetic acid (60 ml.) was added in 4 hr. After the addition of further magnesium (10 g.) the mixture was kept below −20° for 18 hr. Unchanged magnesium was removed, the filtrate neutralized with saturated aqueous sodium carbonate, and acetone removed under a vacuum. The residue formed two layers; the aqueous layer was extracted with ether, and the ether extracts were combined with the organic layer, dried (Na_2SO_4), and distilled. This procedure was repeated four times, and the combined products (64 g., after separation of unchanged mesityl oxide) were redistilled through a 4 in. Stedman column. The fraction, b. p. 44°/0·8 mm., n_D^{22} 1·4601 (9 g.), had infrared and nuclear magnetic resonance spectra almost identical with the spectra of the ether reported above. Gas–liquid chromatography showed the presence of *ca.* 5% of a less volatile impurity. The residue, b. p. >60°/0·5 mm., $n_D^{25.5}$ 1·4693, was treated with 2,4-dinitrophenylhydrazine sulphate in methanol. One of the products was soluble in boiling methanol; it had m. p. 125—126°, undepressed on admixture with the derivative of the ketone (III) obtained above. Kolobielski [3] reports no red 2,4-dinitrophenylhydrazone of this m. p. and gives 109—110° for the m. p. of the derivative of 2-acetyl-1,3,3,4,4-pentamethylcyclopentene.

We are indebted to Dr. L. M. Jackman for assistance in the interpretation of the nuclear magnetic resonance data.

Department of Chemistry, Imperial College of Science and Technology,
S. Kensington, London, S.W.7. [*Received, December 1st*, 1960.]

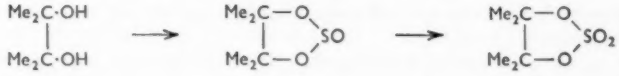
[5] Tiers, *J. Phys. Chem.*, 1958, **62**, 1151.

436. *Tetramethylethylene Sulphate.*

By Wilson Baker and B. F. Burrows.

Cyclic alkylene sulphates have been prepared by four general methods: (*a*) from 1,2- and 1,3-alkylene dibromides and silver sulphate;[1] (*b*) from 1,2- and 1,3-alkanediols with fuming sulphuric acid in chloroform;[2] (*c*) from cyclic sulphites by oxidation with calcium permanganate in acetic acid;[3] and (*d*) from 1,2- and 1,3-diacetoxyalkanes by distillation with dialkyl sulphates.[4] In a few cases other methods have been employed.[2,5]

Ethylene sulphate, previously made by methods (*a*) (22%) and (*d*) (66%), has now also been prepared by method (*c*) in 1% yield. Trimethylene sulphate, previously made by methods (*a*) (29%), (*b*) (10%), and (*d*) (70%), has now similarly been prepared by method (*c*) in 20% yield. Details of these experiments are not recorded because method (*d*) involving transalkylation (published after our work was completed in 1957) is certainly the best for preparing these cyclic sulphates. Tetramethylethylene sulphate (III), which was required for the preparation of highly *C*-methylated compounds, has now been prepared by method (*c*) from pinacol (I) by oxidation of the derived cyclic sulphite (II).[6] Other methods of preparation are complicated by the ease with which pinacol and its derivatives pass into pinacolone or into 2,3-dimethylbuta-1,3-diene.



(I) (II) (III)

Tetramethylethylene sulphate could not be prepared by treating pinacol with sulphuryl chloride in pyridine.

Experimental.—Tetramethylethylene sulphite (II). Anhydrous pinacol is not readily prepared from the hexahydrate by distillation with benzene as recommended in *Organic Syntheses*;[7] large volumes of benzene are required and pinacol is volatile in benzene vapour (pinacol hydrate crystallises from the distillate). Crude pinacol hexahydrate (20 g.) gave anhydrous pinacol, b. p. 168—174°, by the following methods: (*a*) dissolving it in acetone (100 ml.), shaking the solution with anhydrous sodium sulphate (50 g.), and recovery (yield 9·3 g.); (*b*) shaking it with light petroleum (b. p. 60—80°; 40 ml.) and anhydrous potassium carbonate (20 g.) at 40—45° for 10 min. and recovery (yield 7·3 g.); (*c*) distillation at ordinary pressure [yield 6·9 g.; pinacol hydrate (2 g.) was recovered from the filtrate]. The anhydrous pinacol (0·1 mole) was converted into tetramethylethylene sulphite (II) (34% yield) by treatment with purified thionyl chloride (0·2 mole) under the conditions given by Szmant and Emerson;[6] these authors claim a 55% yield but fail to record the relative amounts of the two reactants.

Tetramethylethylene sulphate (III). To tetramethylethylene sulphite (19·6 g.) in acetic acid (60 ml.) was added dropwise with stirring a solution of calcium permanganate (25·5 g.) in water (60 ml.), the temperature being kept below 15°, until, after the first rapid exothermic reaction, an excess of permanganate was present. Sulphur dioxide was now passed in at room temperature to remove manganese dioxide, and after dilution with an equal volume of water, the mixture was extracted three times with ethyl acetate (150, 100, and 50 ml.), and the combined

[1] Baker and Field, *J.*, 1932, 86.
[2] Lichtenberger and Lichtenberger, *Bull. Soc. chim. France*, 1948, **15**, 1002.
[3] Lichtenberger and Hincky, *Bull. Soc. chim. France*, 1951, **18**, 796; Garner and Lucas, *J. Amer. Chem. Soc.*, 1950, **72**, 5499; Brimacombe, Foster, Hancock, Overend, and Stacey, *J.*, 1960, 201.
[4] VEB Filmfabrik Agfa Wolfen, F.P. 1,171,347/1959.
[5] Methylene sulphate, Delépine, *Compt. rend.*, 1899, **129**, 831; *Bull. Soc. chim. France*, 1899, **21**, 1055; Baker, *J.*, 1931, 1765. Glyoxal sulphate, Ott, D.R.-P. 362,743; Ruggli and Henzi, *Helv. Chim. Acta*, 1929, **12**, 364; Baker and Field, *J.*, 1932, 86. See also Lichtenberger and Dürr, *Bull. Soc. chim. France*, 1956, 664. Cyclic sulphates of carbohydrates, prepared by reaction with sulphuryl chloride, Helferich *et al.*, *Ber.*, 1921, **54**, 1082; 1923, **46**, 1083; 1925, **58**, 886; Jones *et al.*, *Canad. J. Chem.*, 1959, **37**, 1412; 1960, **38**, 1122.
[6] Szmant and Emerson, *J. Amer. Chem. Soc.*, 1956, **78**, 454.
[7] *Org. Synth.*, 1942, **22**, 40.

XUM

extracts were shaken with water, then with an excess of aqueous sodium hydrogen carbonate, dried ($CaCl_2$), and distilled under reduced pressure. The remaining product solidified and was crystallised from benzene–light petroleum (b. p. 60—80°) giving *tetramethylethylene sulphate* as needles (yield 11·2 g.), decomp. 131° [Found: C, 39·8; H, 6·7; S (as sulphate by hydrolysis), 17·4. $C_6H_{12}O_4S$ requires C, 40·0; H, 6·7; S, 17·7%].

We thank the Department of Scientific and Industrial Research for a Studentship awarded to B. F. B.

THE UNIVERSITY, BRISTOL. [*Received, December 5th*, 1960.]

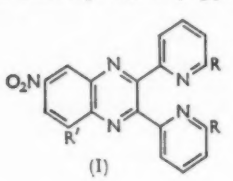
---

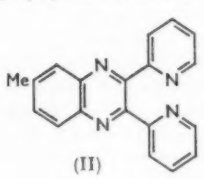
437. *Carcinogenic Nitrogen Compounds. Part XXX.*[1] *2,3-Dipyridylquinoxalines and 5,6-Dipyridylpyrido(2′,3′-2,3)pyrazines.*

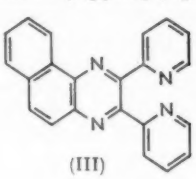
By NG. PH. BUU-HOÏ and G. SAINT-RUF.

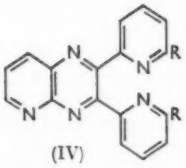
CARCINOGENIC substances have often been encountered among heterocyclic molecules containing several nuclear nitrogen atoms, *e.g.*, dinaphthopyrazines,[2] which produce bladder tumours and sarcomas, and tricycloquinazoline, which is carcinogenic in mice both on injection and on skin-painting.[3] The present Note reports the synthesis of some polycyclic compounds bearing the pyrazine nucleus and pyridyl substituents, prepared for biological testing.

Condensation of 4-nitro-1,2-phenylenediamine with 2,2′-pyridil and 6,6′-dimethyl-2,2′-pyridil in ethanol yielded 6-nitro-2,3-di-(2-pyridyl)- (I; R = R′ = H) and 6-nitro-2,3-di-(6-methyl-2-pyridyl)-quinoxaline (I; R = Me, R′ = H) respectively. Similar condensations of 2,2′-pyridil with 4-methyl- and 3-chloro-5-nitro-1,2-phenylenediamine afforded 6-methyl-2,3-di-(2-pyridyl)- (II) and 5-chloro-7-nitro-2,3-di-(2-pyridyl)-quinoxaline (I; R = Me, R′ = Cl); 1,2-naphthylenediamine and 2,2′-pyridil gave 2,3-di-(2-pyridyl)-5,6-benzoquinoxaline (III). Whilst the above condensations all took place in a matter of minutes, 2,3-diaminopyridine reacted sluggishly, and 5,6-di-(2-pyridyl)- (IV; R = H) and 5,6-di-(6-methyl-2-pyridyl)-pyrido(2′,3′-2,3)pyrazine (IV; R = Me) were obtained only after several hours' heating.


(I)


(II)


(III)


(IV)

In preliminary tests in rats, the compounds of type (I) showed considerable toxicity towards the liver when given by injection.

[1] Part XXIX, Marty, Buu-Hoï, and Jacquignon, *J.*, 1961, 384.
[2] Rudali, Chalvet, and Winternitz, *Compt. rend.*, 1955, **240**, 1738; Hackmann, *Z. Krebsforschung*, 1951, **58**, 56.
[3] Baldwin, Butler, Cooper, and Partridge, *Nature*, 1958, **181**, 838; Baldwin, Cunningham, and Partridge, *Brit. J. Cancer*, 1959, **13**, 94.

Experimental.—*6-Nitro-2,3-di-(2-pyridyl)quinoxaline.* A solution of 2,2′-pyridil (10 g.) and 4-nitro-1,2-phenylenediamine (7 g.) in ethanol (150 c.c.) was refluxed for 45 min. The orange solid formed on concentration of the solution and cooling was collected and recrystallised from ethanol in presence of charcoal to remove the red impurity, giving the *quinoxaline* as yellowish prisms (12 g.), m. p. 193° (Found: N, 21·0. $C_{18}H_{11}N_5O_2$ requires N, 21·3%).

6-Nitro-2,3-di-(6-methyl-2-pyridyl)quinoxaline, similarly obtained from 6,6′-dimethyl-2,2′-pyridil (10 g.) and 4-nitro-1,2-phenylenediamine (6·3 g.) in ethanol (150 c.c.), formed pale yellow needles (13 g.), m. p. 191°, from ethanol–benzene (Found: C, 66·9; H, 4·5; N, 19·4. $C_{20}H_{15}N_5O_2$ requires C, 67·2; H, 4·2; N, 19·6%).

6-Methyl-2,3-di-(2-pyridyl)quinoxaline, prepared from 2,2′-pyridil (6 g.) and 4-methyl-1,2-phenylenediamine (3·5 g.) in ethanol (100 c.c.), crystallised as colourless prisms (7·5 g.), m. p. 142°, from cyclohexane (Found: C, 76·4; H, 5·0; N, 18·6. $C_{19}H_{14}N_4$ requires C, 76·5; H, 4·7; N, 18·8%).

5-Chloro-7-nitro-2,3-di-(2-pyridyl)quinoxaline, obtained from 2,2′-pyridil (10 g.) and 3-chloro-5-nitro-1,2-phenylenediamine (9 g.) in ethanol (150 c.c.), formed yellow needles (15 g.), m. p. 194°, from ethanol (Found: N, 19·0. $C_{18}H_{10}ClN_5O_2$ requires N, 19·2%).

2,3-Di-(2-pyridyl)-5,6-benzoquinoxaline. A solution of 2,2′-pyridil (2 g.) and 1,2-naphthylenediamine (1·5 g.) in ethanol (50 c.c.) was refluxed for 3 hr., the solvent distilled, and the residue crystallised from cyclohexane, giving colourless prisms (2 g.), m. p. 146° (Found: C, 79·0; H, 4·2; N, 16·6. $C_{22}H_{14}N_4$ requires C, 79·0; H, 4·2; N, 16·7%).

5,6-Di-(2-pyridyl)pyrido(2′,3′-2,3)pyrazine. 2,3-Diaminopyridine (m. p. 112°) was prepared from 2-amino-3-nitropyridine by Tschitschibabin and Kirssanow's method; [4] a solution of this diamine (3 g.) and 2,2′-pyridil (5·8 g.) in ethanol (50 c.c.) was refluxed for 18 hr., and the solvent was distilled off; the residue recrystallised from heptane as colourless needles (5 g.), m. p. 146° (Found: C, 71·4; H, 4·2; N, 24·3. $C_{22}H_{11}N_5$ requires C, 71·6; H, 3·9; N, 24·6%). When the heating was reduced to 45 min., no condensation product could be isolated and the reagents were mostly recovered.

5,6-Di-(6-methyl-2-pyridyl)pyrido(2′,3′-2,3)pyrazine, similarly obtained from 2,3-diaminopyridine (1·5 g.) and 6,6′-dimethyl-2,2′-pyridil (3·3 g.) in ethanol (25 c.c.), formed colourless prisms (3 g.), m. p. 155°, from heptane (Found: C, 72·5; H, 5·0; N, 22·2. $C_{19}H_{15}N_5$ requires C, 72·7; H, 4·8; N, 22·4%).

This investigation was supported in part by a research grant from the National Cancer Institute of the National Institutes of Health, U.S. Public Health Service; the authors thank the authorities concerned.

THE RADIUM INSTITUTE, THE UNIVERSITY OF PARIS. [*Received, December 7th*, 1960.]

[4] Tschitschibabin and Kirssanow, *Ber.*, 1927, **60**, 766.

---

438. *Bis(triphenylphosphine)nickel Dinitrosyl.*

By W. P. GRIFFITH, J. LEWIS, and G. WILKINSON.

BIS(TRIPHENYLPHOSPHINE)NICKEL DICARBONYL has been found to react with nitric oxide in benzene solution, to give a dark purple crystalline complex $[(C_6H_5)_3P]_2Ni(NO)_2$. The compound has been shown to be diamagnetic, monomeric in benzene, and a non-electrolyte in nitrobenzene. In the infrared spectrum there is only one sharp N–O stretching frequency, at 1745 cm.$^{-1}$, in the region characteristic for NO^+ co-ordination complexes.[1,2] Isotopic substitution, by use of ^{15}NO, has shown this frequency to move to 1706 cm.$^{-1}$, which agrees very well with the calculated ($\sqrt{30/31}$) displacement to 1705 cm.$^{-1}$. Since only one frequency is observed, and it has not been possible to resolve this band, even on a grating instrument, for chloroform and carbon tetrachloride solutions, the possibility of two equivalent co-ordinated NO^+ groups in a tetrahedral or a *cis*-planar structure can be excluded. If the molecule is tetrahedral, the observations are consistent only with the

[1] Lewis, Irving, and Wilkinson, *J. Inorg. Nuclear Chem.*, 1958, **7**, 32.
[2] Griffith, Lewis, and Wilkinson, *J. Inorg. Nuclear Chem.*, 1958, **7**, 38.

XUM

requirement that the other NO group is present as a co-ordinated NO^- group. However, no absorption in the region characteristic of NO^- groups [2] was observed owing to intense absorption by the triphenylphosphine ligand in this region. A possible formulation as a planar *trans*-structure was excluded as the complex was found to have a dipole moment of 4·26 D (at 30°) in benzene, which may be compared with the dipole moment [3] of the tetrahedral bis(triphenylphosphine)nickel dicarbonyl of 3·82 D. From *X*-ray powder patterns, we have shown, however, that the dicarbonyl and the nitrosyl compounds are not isomorphous. On the present formulation for the dinitrosyl the nickel is formally in the zero oxidation state with a tetrahedral stereochemistry for the molecule.

This nickel nitrosyl compound can thus be considered as the parent of the triphenylphosphinenickel nitrosyl bromide, $[(C_6H_5)_3P]_2NiNOBr$,[4] where the N–O stretching frequency occurs at 1735 $cm.^{-1}$, in which the NO^- is replaced by Br^-.

We also prepared the corresponding triphenyl phosphite dinitrosyl complex where the N–O stretching frequency appears at 1710 $cm.^{-1}$; similar products were obtained by the action of nitric oxide on tributyl- and tripropyl-phosphinenickel dicarbonyls, but the purple products were oils and could not be obtained analytically pure.

The situation in which an identical ligand molecule, *i.e.*, NO, can be bound simultaneously to an atom in a radically different way is somewhat unusual, and it might have been expected that by some electronic mechanism the two groups would have been made equivalent. It has been recently suggested,[5] on the basis of ultraviolet absorption spectra, that in the red nitrosopentamminecobalt derivatives, where the nitric oxide was considered to be bound as NO^- from the infrared criterion,[2] that the nitric oxide may be bound through the oxygen atom, *i.e.*, as Co–O–N. The inequivalence of the two NO groups in the dinitrosyl nickel derivatives can thus be readily understood, although there is at the present time no unequivocal evidence to favour bonding through oxygen.

Experimental.—Microanalyses and molecular-weight determinations (ebullioscopic in benzene) were made by the Microanalytical Laboratory of this College.

Preparations. Bis(triphenylphosphine)nickel dicarbonyl (4 g.) in anhydrous benzene (80 ml.) was treated with nitric oxide for 3 hr. The purple product, *bis(triphenylphosphine)-nickel dinitrosyl*, was recrystallised from light petroleum (b. p. 40—60°)–benzene and dried *in vacuo* (yield, 3 g., 70%) (Found: C, 66·7; H, 4·5; N, 4·3; P, 9·2; Ni, 8·9%; *M*, 648. $C_{36}H_{30}N_2NiO_2P_2$ requires C, 67·2; H, 4·7; N, 4·4; P, 9·7; Ni, 9·1%; *M*, 642). The complex is stable in air and is unaffected by dilute acids. It is readily soluble in benzene, chloroform, alcohol, and similar solvents, the solutions slowly decomposing in air, especially those in chlorinated solvents.

In a similar manner, *bis(triphenyl phosphite)nickel dinitrosyl* (Found: C, 57·9; H, 4·6; N, 3·8; Ni, 8·2. $C_{36}H_{30}N_2NiO_8P_2$ requires C, 58·8; H, 4·1; N, 3·8; Ni, 8·0%) was prepared.

The isotopically substituted triphenylphosphine compound was prepared by using ^{15}NO (66%) prepared from the reaction of potassium nitrite with sulphuric acid and potassium iodide.

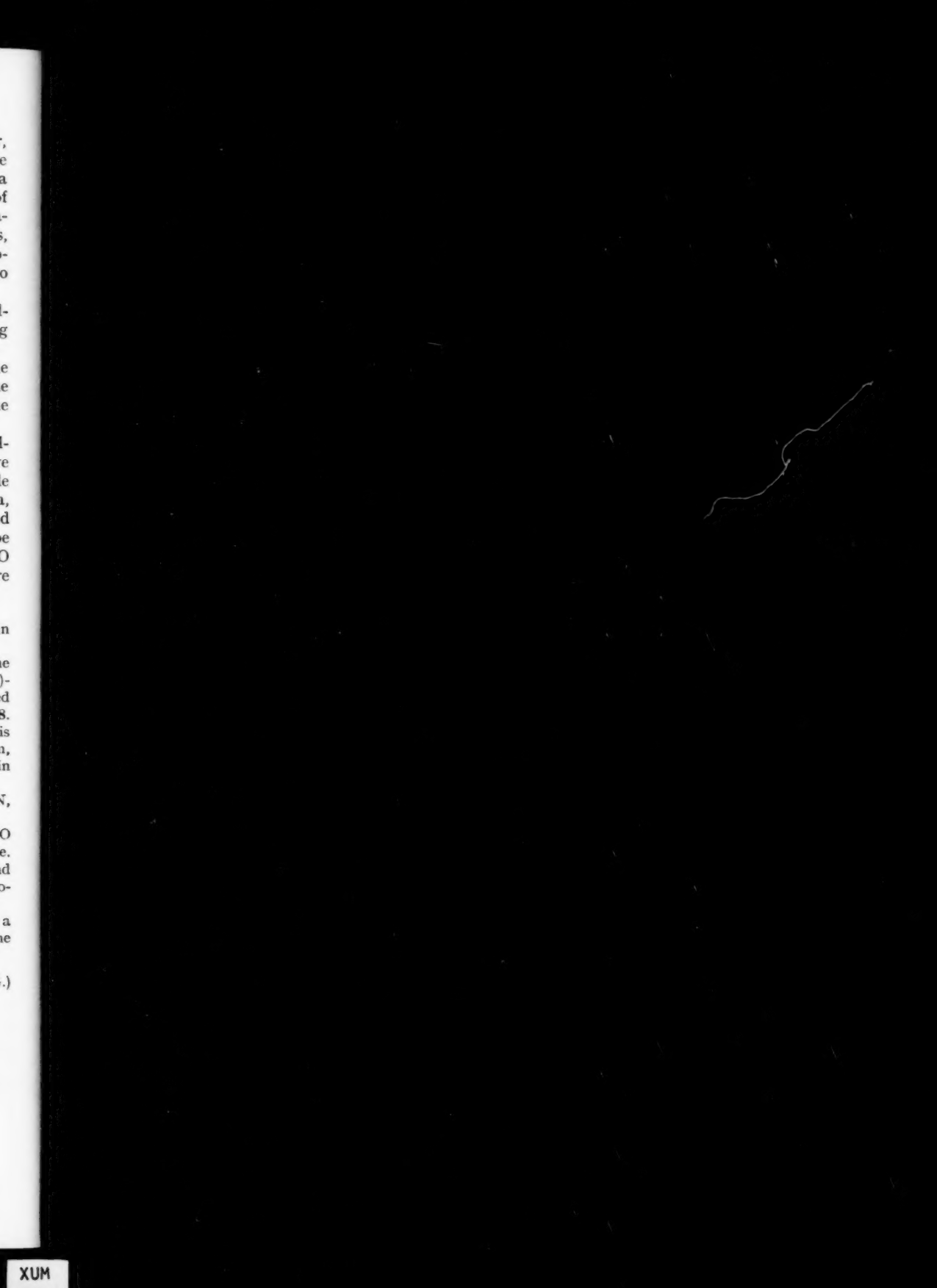
Physical measurements. Infrared spectra were measured on Perkin–Elmer model 21 and Grubb–Parsons grating instruments for Nujol mulls and for carbon tetrachloride and chloroform solutions.

The dipole moment was measured for benzene solution (seven concentrations) by means of a standard heterodyne-beat-type instrument with a modified Sayce–Briscoe cell, and the procedure described previously.[6]

We thank the Department of Scientific and Industrial Research for a studentship (W. P. G.) and the Hercules Powder Co. for research expenses.

INORGANIC CHEMISTRY RESEARCH LABORATORIES,
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY,
LONDON, S.W.7.

[*Received, December 15th,* 1960.]

[2] Chatt and Hart, *J.*, 1960, 1378.
[4] Feltham, *J. Inorg. Nuclear Chem.*, 1960, **14**, 307.
[5] Yamada, Nishikawa, and Tsuchida, *Bull. Chem. Soc. Japan*, 1960, **33**, 930.
[6] Burton, Pratt, and Wilkinson, *J.*, 1960, 4290.

XUM